# LCLS-II design status and challenges

Nikolay Solyak (from LCLS-II team)

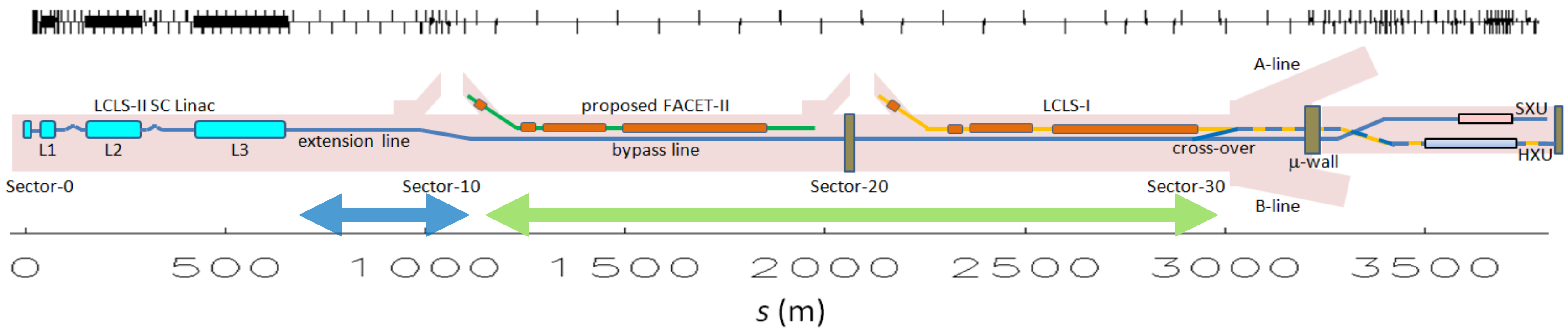
AD meeting, March 10, 2015

# Outline

- Scope and overall Status of LCLS-II project
- LCLS-II layout and parameters
  - Injector baseline/alternatives
  - Beam optics and challenges
- Fermilab scope of work and status of design
  - Cryogenic loads from wakes/RF heating
  - Results of high-Q0 program (overview)
- CM and components designs (1.3 and 3.9 GHz)

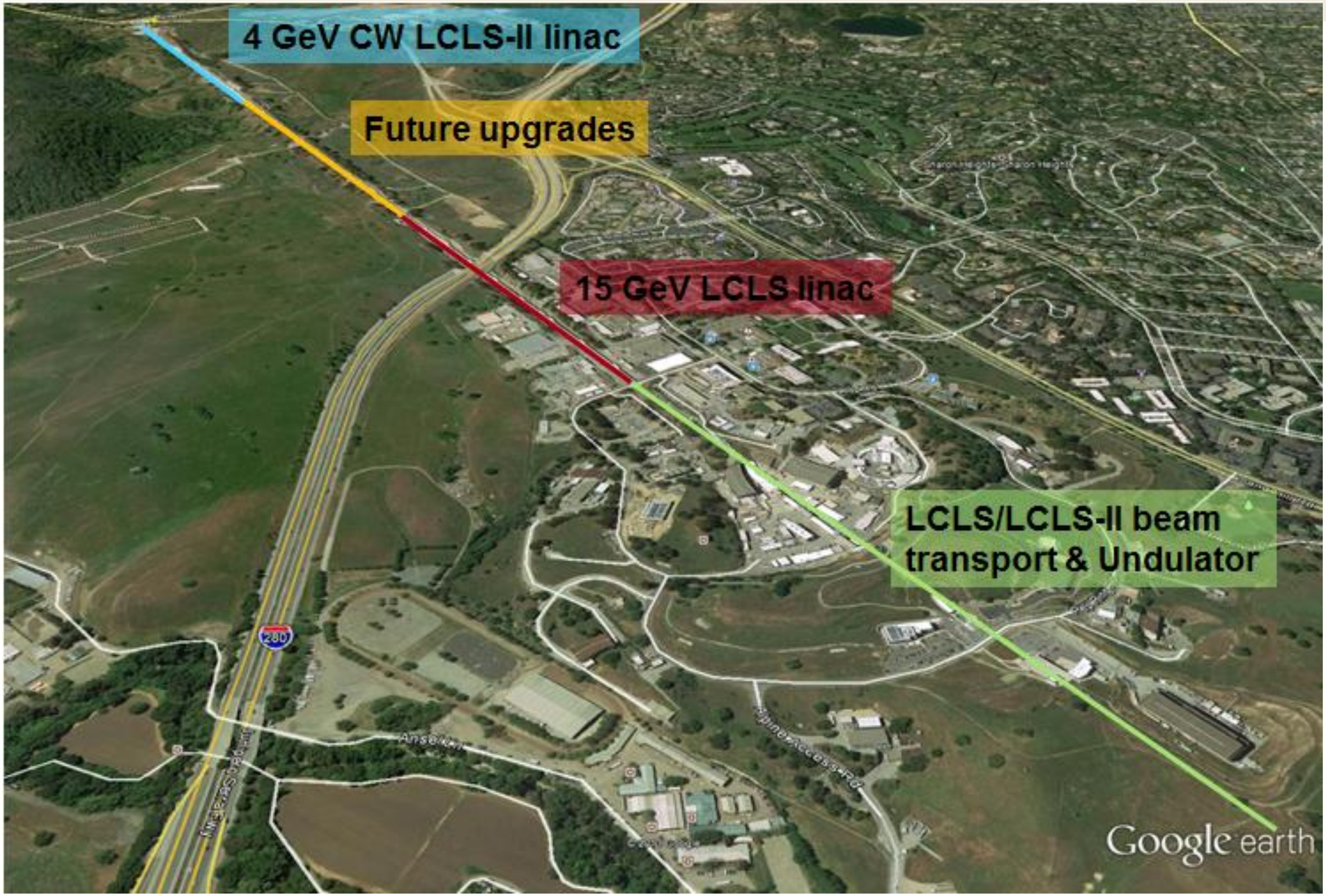
  \- (helium vessel /Tuner/magnet/Coupler/HOM coupler,…)
- Design verification program and first results
- CMTS status and plans
- Summary

# LCLS-II Project Scope



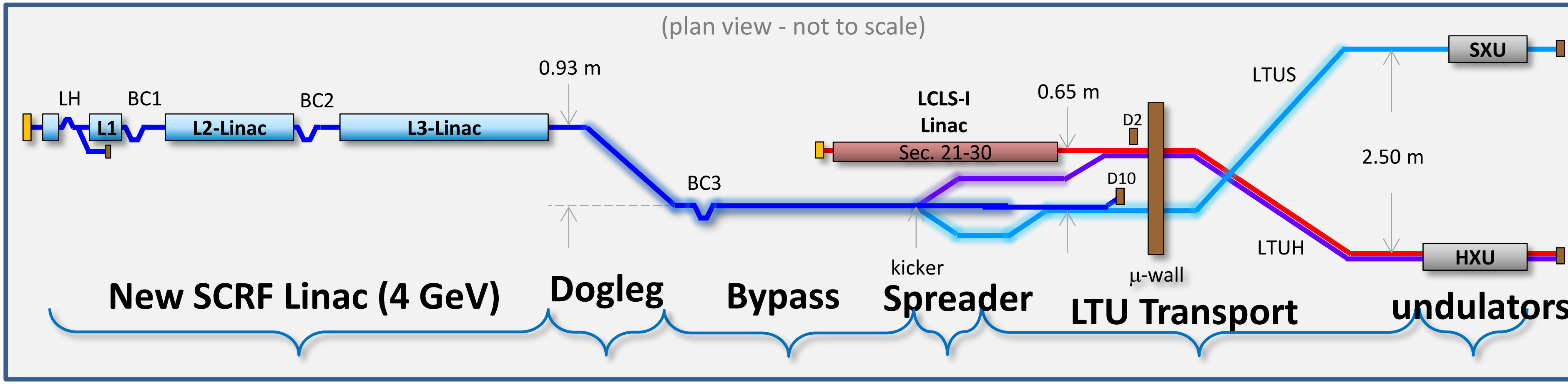

- New Injector, SCRF linac, and extension installed in Sectors 0-10
- Re-use existing Bypass line from Sector 10 → BSY
- Install new variable gap HXR (replacing LCLS-I) and SXR
- Re-use existing Linac-to-Undulator line (LTU) to new variable gap hard x-ray undulator (HXU); modify e-beam dump for higher power
- Construct new LTU to Soft x-ray undulator (SXU) and new dump
- Re-use existing high power dump in BSY, add fast fan-out deflector to direct beams to dump, SXU or HXU
- Modify existing LCLS-I X-ray optics and build new SXR X-ray line

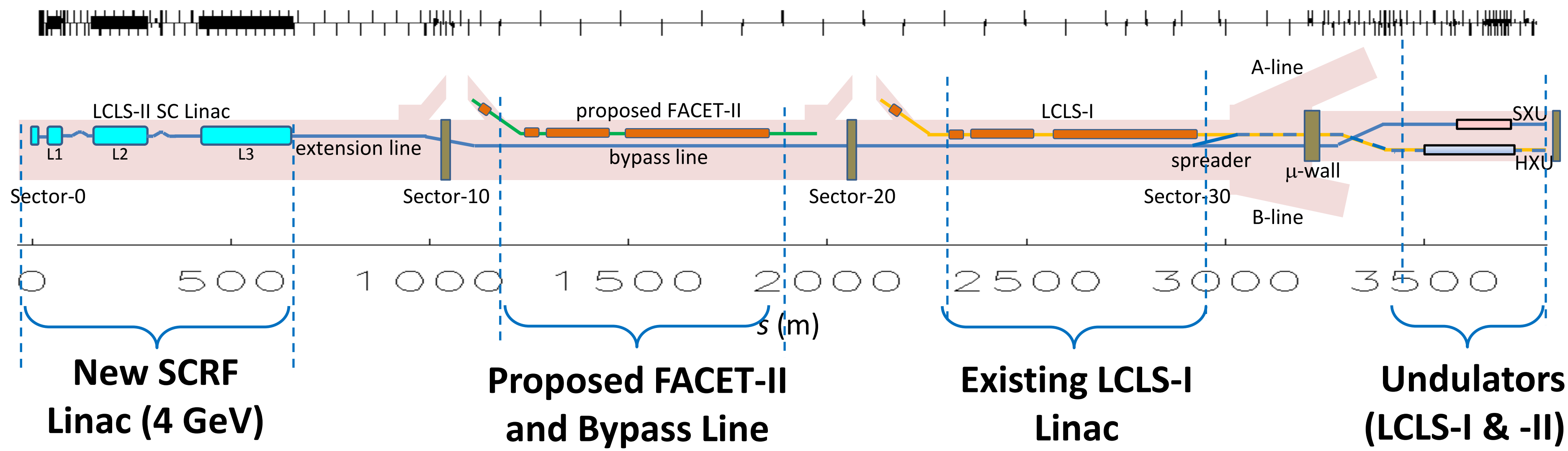
# LCLS-II Concept
## Use 1st km of SLAC linac for CW SCRF linac



See PRD: *LCLSII-2.5-PR-0134*

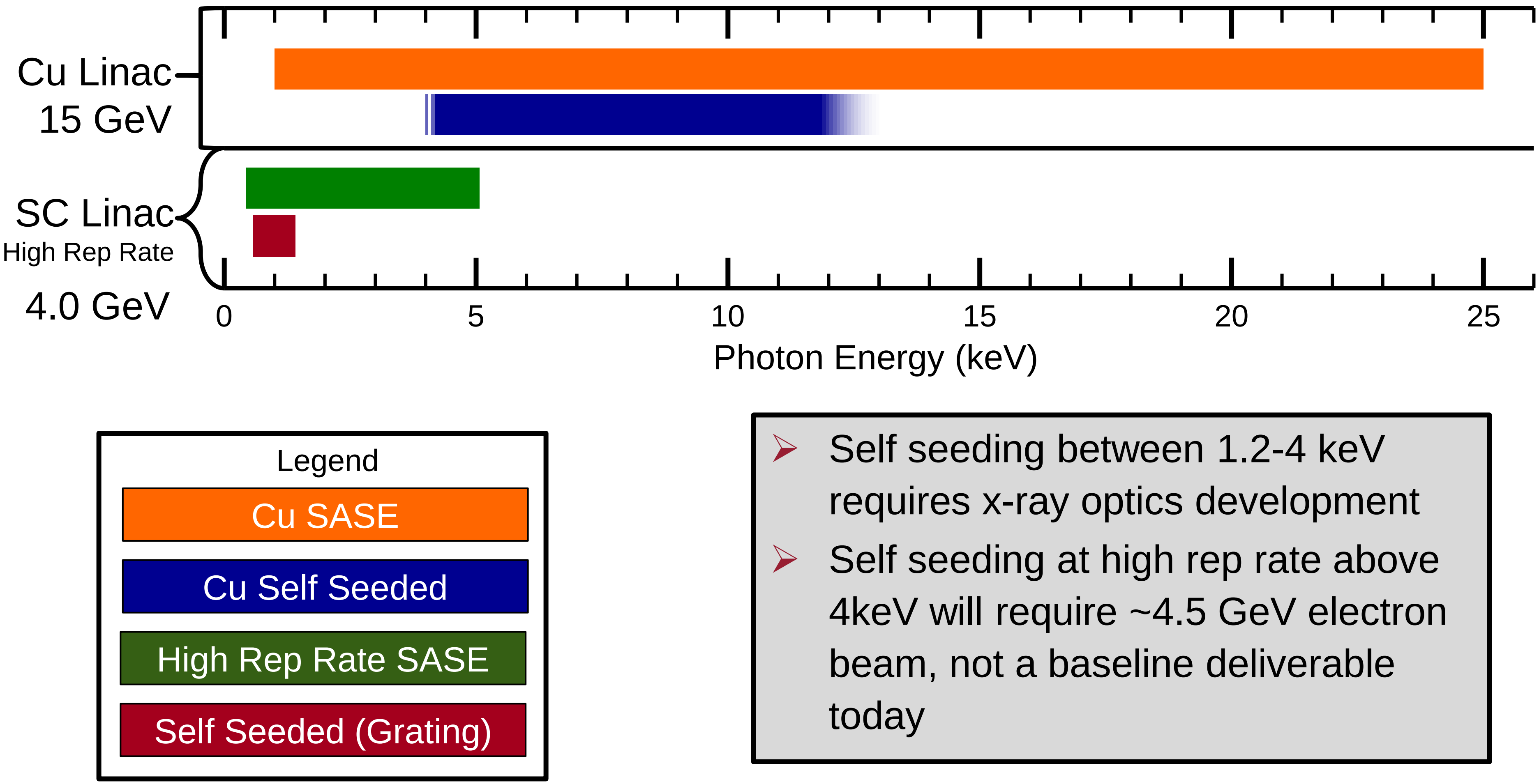
# LCLS-II Layout



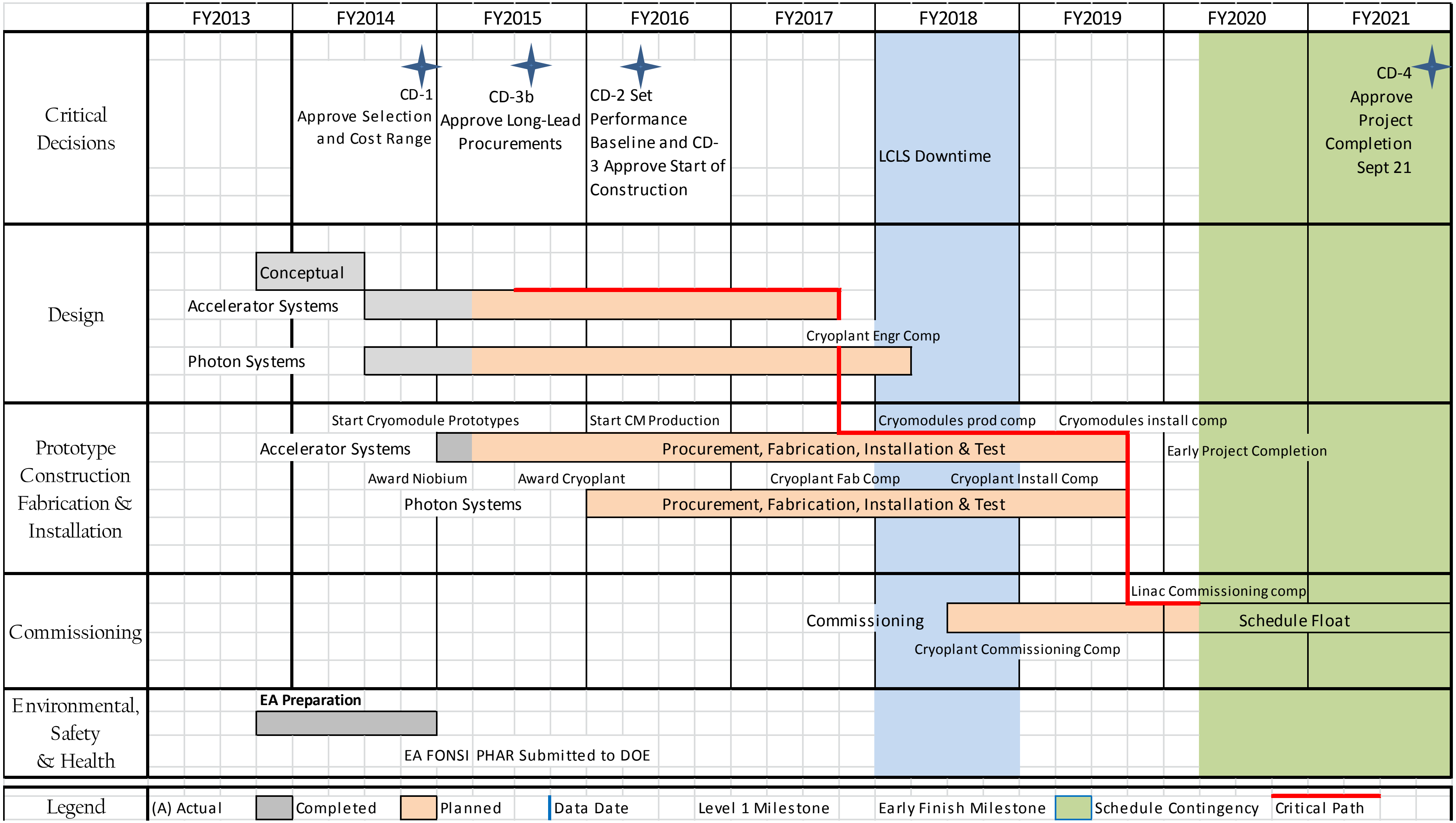

Approximately in scale

# Revised LCLS-II (Phase II) Baseline Deliverables




- Self seeding between 1.2-4 keV requires x-ray optics development
- Self seeding at high rep rate above 4keV will require ~4.5 GeV electron beam, not a baseline deliverable today

# Schedule, Major Milestones, Critical Path



# Project Collaboration: SLAC couldn't do this without…

| | |
|---|---|
| Fermilab | • 50% of cryomodules: 1.3 GHz<br>• Cryomodules: 3.9 GHz<br>• Cryomodule engineering/design<br>• Helium distribution<br>• Processing for high Q (FNAL-invented gas doping) |
| Jefferson Lab<br>EXPLORING THE NATURE OF MATTER | • 50% of cryomodules: 1.3 GHz<br>• Cryoplant selection/design<br>• Processing for high Q |
| BERKELEY LAB | • Undulators<br>• $e^-$ gun & associated injector systems |
| Argonne<br>NATIONAL LABORATORY | • Undulator Vacuum Chamber<br>• Also supports FNAL w/ SCRF cleaning facility<br>• Undulator R&D: vertical polarization |
| CORNELL UNIVERSITY<br>FOUNDED A.D. 1865 | • R&D planning, prototype support<br>• processing for high-Q (high Q gas doping)<br>• $e^-$ gun option |

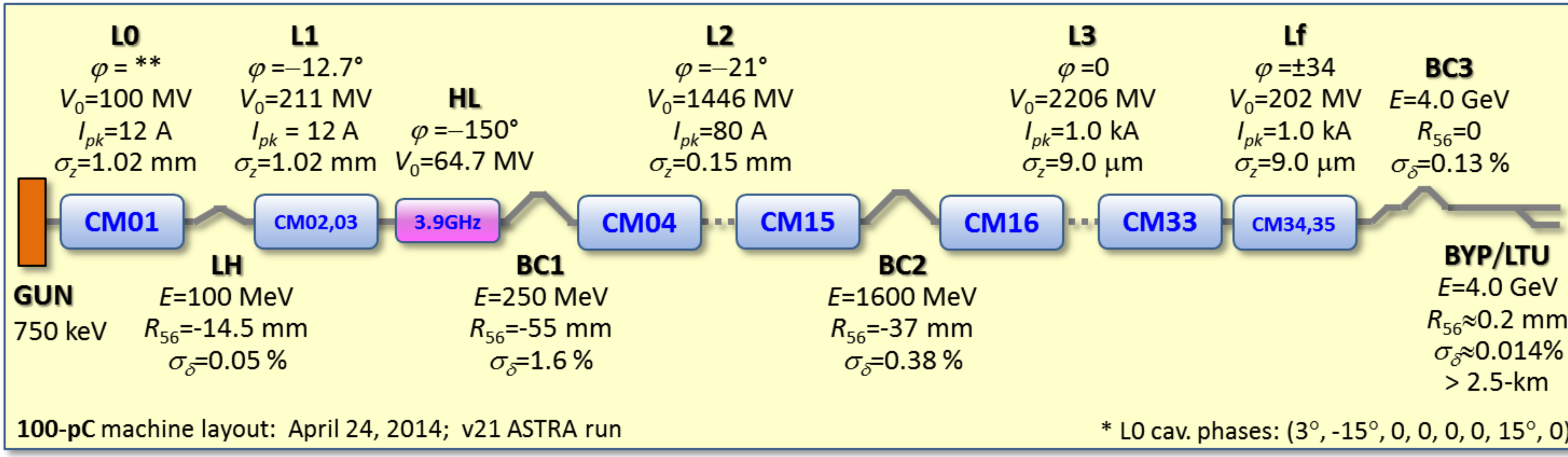
# SCRF Linac Design

# LCLS-II (SCRF) Baseline Parameters

| Parameter | symbol | nominal | range | units |
|---|---|---|---|---|
| Electron Energy | $E_f$ | **4.0** | 2.0 - 4.14 | GeV |
| Bunch Charge | $Q_b$ | **100** | 10 - 300 | pC |
| Bunch Repetition Rate in Linac | $f_b$ | **0.62** | 0 - 0.93 | MHz |
| Average $e^-$ current in linac | $I_{avg}$ | **0.062** | 0.0 - 0.3 | mA |
| Avg. $e^-$ beam power at linac end | $P_{av}$ | **0.25** | 0 - 1.2 | MW |
| Norm. rms slice emittance at undulator | $\gamma\varepsilon_{\perp\text{-}s}$ | **0.45** | 0.2 - 0.7 | µm |
| Final peak current (at undulator) | $I_{pk}$ | **1000** | 500 - 1500 | A |
| Final slice E-spread (rms, w/heater) | $\sigma_{Es}$ | **500** | 125 - 1500 | keV |
| RF frequency | $f_{RF}$ | **1.3** | - | GHz |
| Avg. CW RF gradient (powered cavities) | $E_{acc}$ | **16** | - | MV/m |
| Avg. Cavity Q0 | $Q0$ | **2.7e10** | 1.5 - 5e10 | - |
| Photon energy range of SXR (**SCRF**) | $E_{phot}$ | - | **0.2 - 1.3** | keV |
| Photon energy range of HXR (**SCRF**) | $E_{phot}$ | - | **1 - 5** | keV |
| Photon energy range of HXR (**Cu-RF**) | $E_{phot}$ | - | **1 - 25** | keV |
| | | 240kW | 0-1.2MW | |

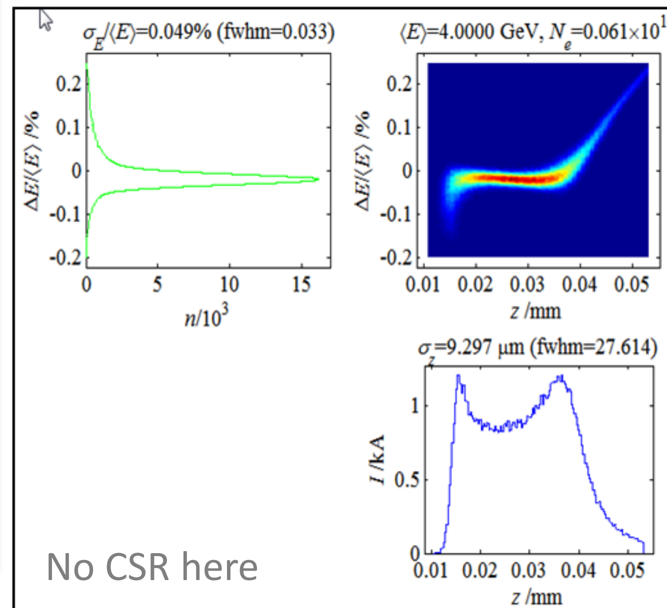
See PRD:
*LCLSII-2.4-PR-0041*

# Linac RF and Compression




| Linac Sec. | $V_0$ (MV) | $\varphi$ (deg) | Acc. Grad.* (MV/m) | No. Cryo Mod's | No. Avail. Cav's | Spare Cav's | Cav's per Amp. |
|---|---|---|---|---|---|---|---|
| L0 | 100 | ** | 16.3 | 1 | 8 | 1 | 1 |
| L1 | 211 | -12.7 | 13.6 | 2 | 16 | 1 | 1 |
| HL | -64.7 | -150 | 12.5 | 2 | 16 | 1 | 1 |
| L2 | 1446 | -21.0 | 15.5 | 12 | 96 | 6 | 48 |
| L3 | 2206 | 0 | 15.7 | 18 | 144 | 9 | 48 |
| Lf | 202 | ±34 | 15.7 | 2 | 16 | 1 | 1 |

Includes 2.5-km RW-wakes




* Nom. crest grads. averaged over powered cavities (worst phasing requires 16 MV/m)

** L0 cav. phases: ~(3°, –15°, 0, 0, 0, 0, 15°, 0), with cav1 at 70% & cav2 at 21% of cav-3-7 grads.

April 24, 2014 – P. Emma (100 MeV injector, 150-μm bunch length after BC1, -37-mm BC2 $R_{56}$)

# LCLS-II CW Injector Options

At 4 GeV, brightness is critical for FEL performance

Options for MHz source:

- DC Gun with laser photocathode (Cornell)
- UHF Gun operating at sub-harmonic (LBNL)
- SRF multi-cell gun
- Different benefits/risks for each

Injector team is evaluating options (John Schmerge)

- CDR baseline is 750 kV LBNL APEX gun
  - LBL APEX R&D program aiming for FY15 brightness demonstration
- Will demonstrate ~500 kV DC gun in FY15 as well
- Large team (Cornell, FNAL, LBNL, SLAC) simulating different configurations

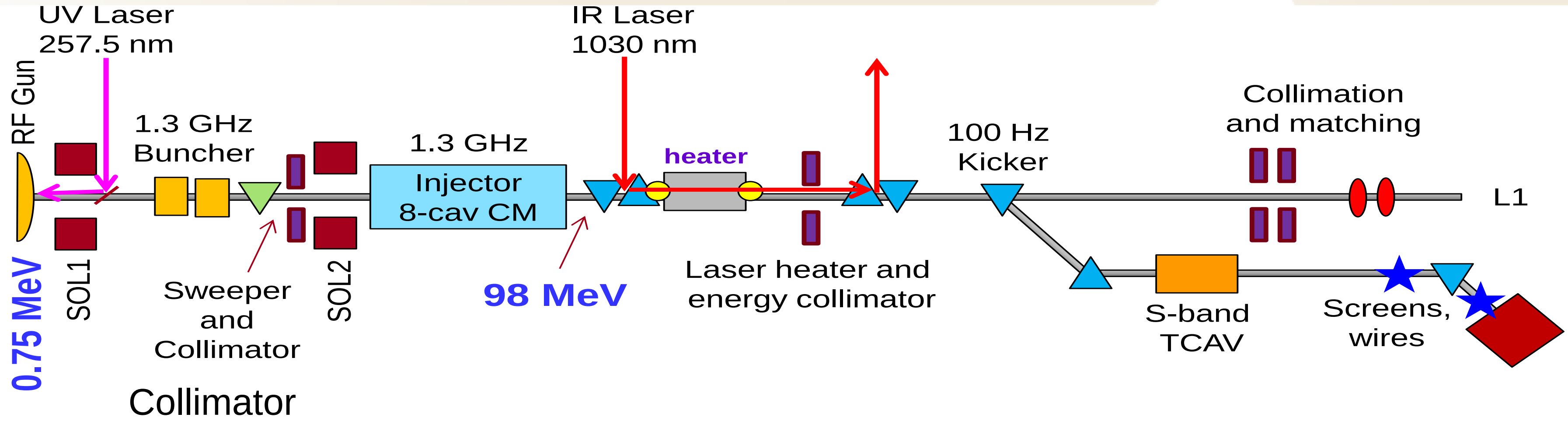
See LCLSII-2.2-PR-0084, LCLS-II SCRF Injector System

# Major challenges of the LCLS-II

- **SCRF LInac is based on XFEL/ILC technology, but utilize 100% duty cycle**
- **Some studies/experience  on extension of this technology to high rep. rate or cw are at HZB/BESSY, Cornell,  JLAB and DESY**

- High gradient (16MV/m) at CW regime:
  - High dynamic heat loads in CM   ~10W→ ~100W
    - High Q0 R&D to reduce cryogenic loads
  - Redesign of the some components: CM, coupler, HOM, tuner, helium vessel, magnetic shielding, …
  - Dark current and Radiation
- High beam power  (1.2 MW; 0.3mA x 4 GeV); phase I $P_b$=240kW
  - Collimation system and diagnostics
- Very short bunch length  ~ 9 µm, $I_{pk}$ ~ 1kA
  - Wakefields, heating of the cavities and beampipes, BLA
- Very low emittances (at undulators)
  - Preservation of low emittances from injector to the end
- Low injection energy (350-700 keV)
  - Sensitivity to misalignments/errors/field imperfections/

# Injector Baseline Layout

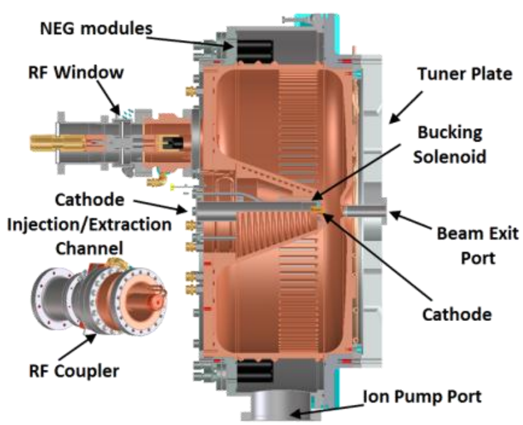



## Gun Options:

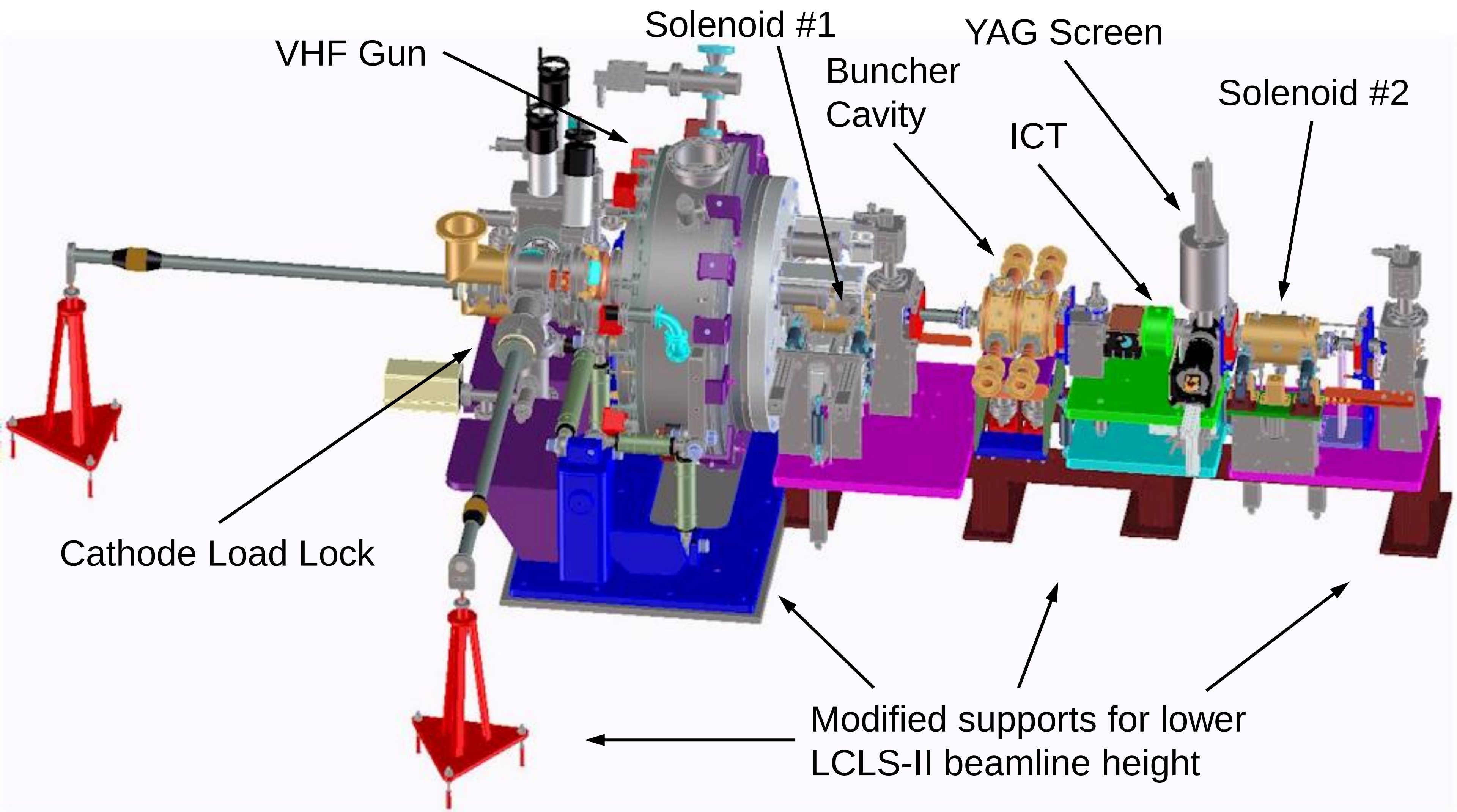
- **APEX (LBNL)** – RF photo gun, NC, 186MHz, 750kV, 100-300pC
- **Cornell DC gun;** photocathode (350kV)

APEX

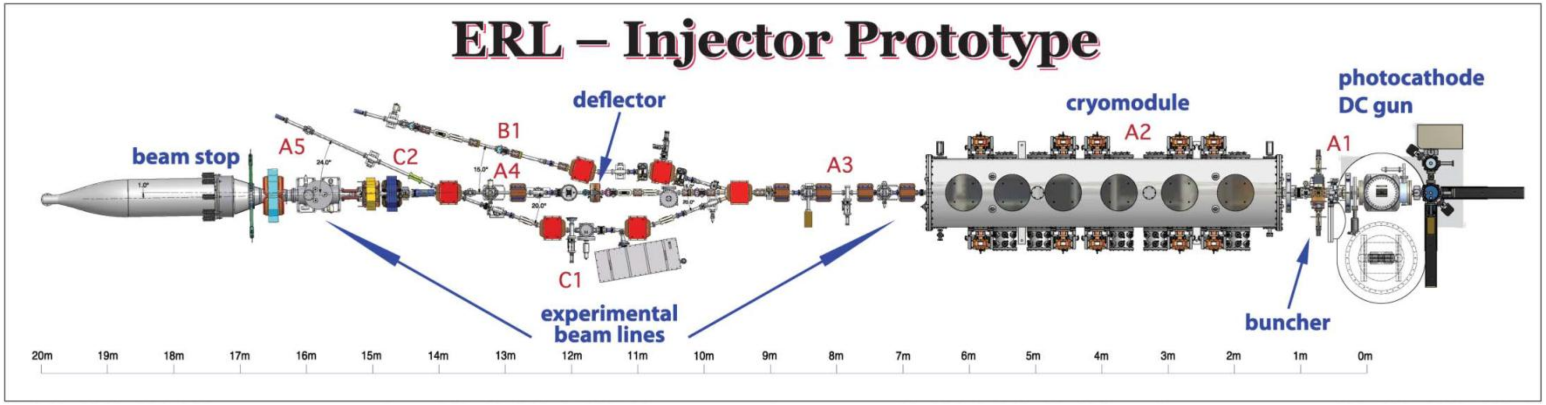
- CW (up to 1 MHz), 0.4/0.6 μm emittance @100/300 pC
- Major injector components (APEX):
  - NC 185.7 MHz RF gun
  - Cs2Te cathode; UV/IR lasers for cathode/laser heater
  - NC 1.3 GHz buncher; two solenoids
  - SC 1.3 GHz 8-cavity CM (energy up to 100 MeV)



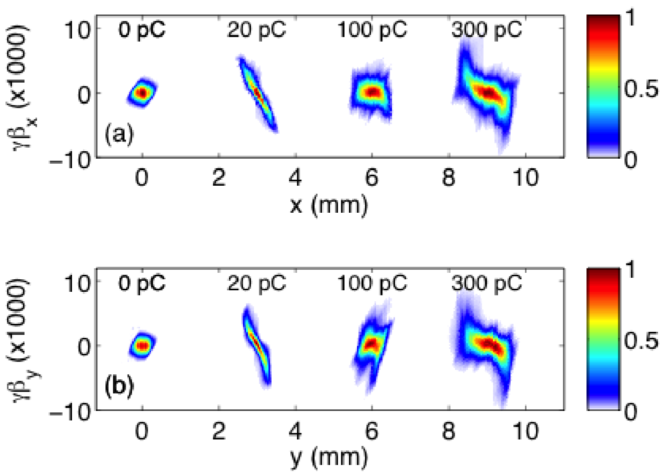
# Injector Source (GunB) Layout

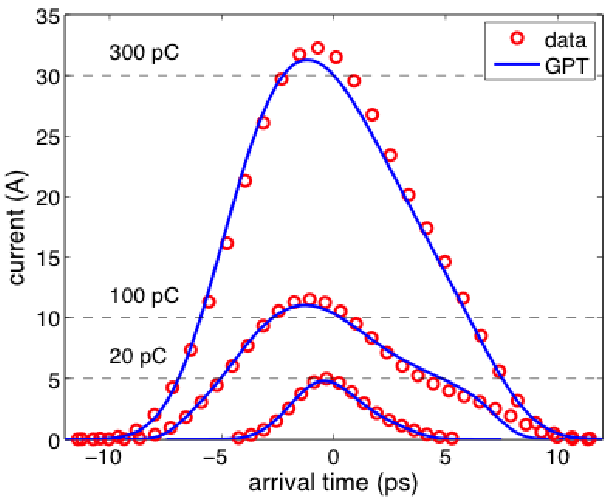


# CW Injector Feasibility R&D
## Nominal parameters demonstrated at Cornell



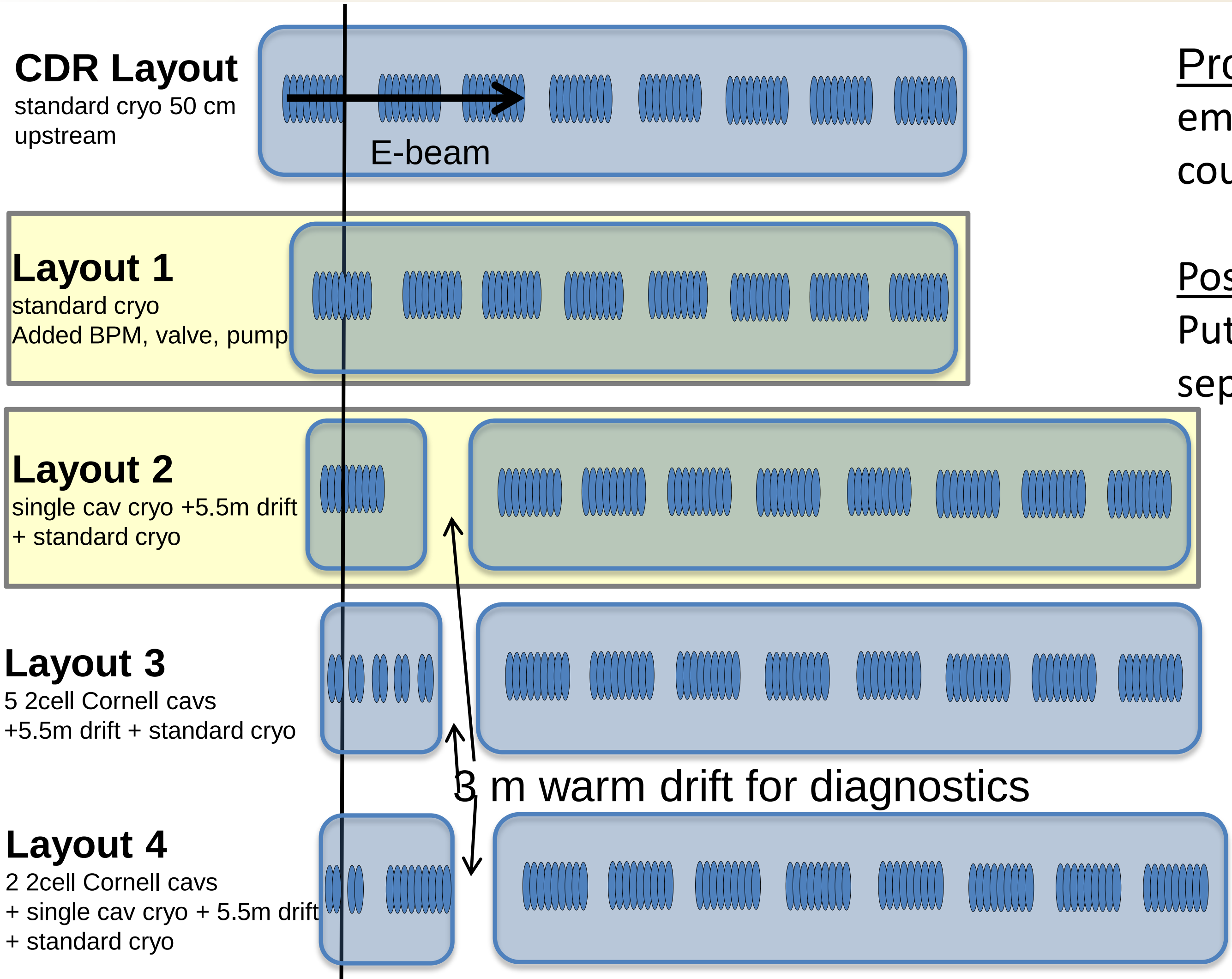

| Bunch charge | Peak current | Emittance (95%) |
|---|---|---|
| 20 pC | 5 A | 0.25 μm |
| 100 pC | 10 A | 0.4 μm |
| 300 pC | 30 A | 0.6 μm |




C. Guilliford, *et al*, http://arxiv.org/abs/1501.04081( 2015)

# Injector Layout Options Simulated



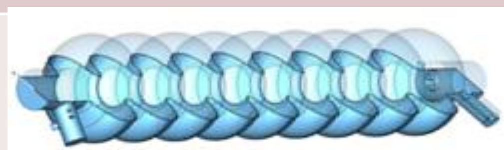
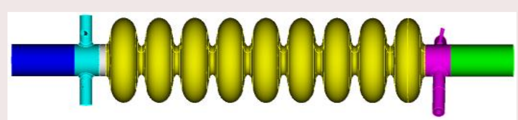

<u>Problem:</u>
emittance growth due to coupler kick:

<u>Possible Solution</u>
Put special cavity w/o kick in separate CM

Cornell, FNAL, LBNL and SLAC are engaged in the simulations.

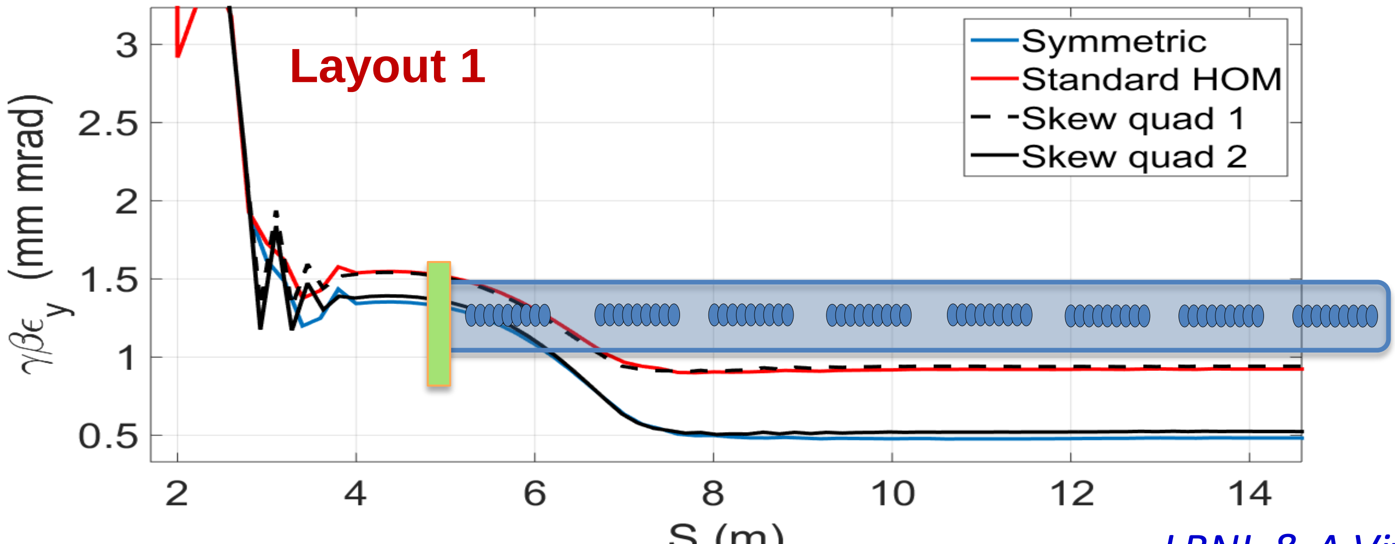
# HOM Coupler Options and Results at 300 pC

- HOM/power couplers field asymmetries are a major concern for emittance degradation at low energy (<1 MeV)
- Options 2, 3 & 4 produce equally good results (emit. spec at 100/300 pC is 0.4/0.6 microns)
- Decision likely determined by engineering consideration

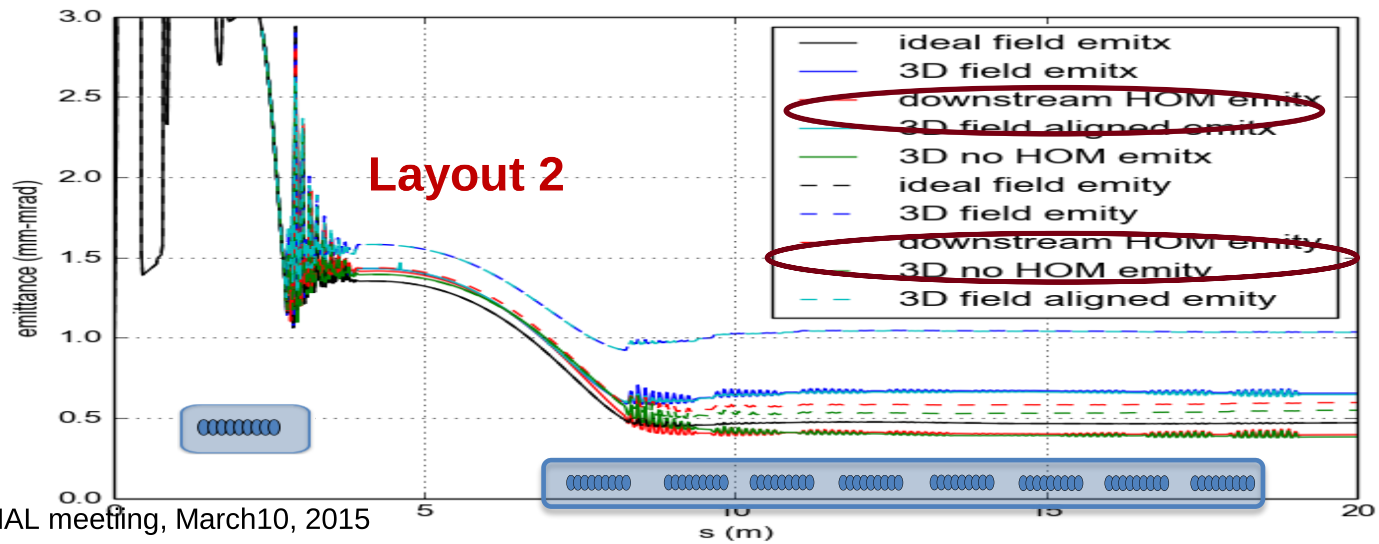
| Couplers arrangement | | CDR layout: ε (μm) 100% | Alternate layout: ε (μm) 100% |
|---|---|---|---|
| **Option 0:** Upstream: No HOM downstream: No HOM & No FPC | "Ideal" 2D cavity | 0.49 | 0.45 |
| **Option 1:** Standard ILC 9-cell cav 1 HOM upstream, 1 HOM/1 FPC downstream |  | 0.66 | 1.04 |
| **Option 2**: No HOM upstream, 2 HOMs downstream and 1 FPC downstream (A.Lunin/FNAL) |  | 0.58 | 0.60 |
| **Option 3**: 2 HOMs upstream, and 1 HOM/power couplers downstream (Z. Li/SLAC) |  | 0.57 | Under study |
| **Option 4**: No HOM upstream (beam absorbers), 1 FPC downstream (Cornell) | | 0.55 | 0.55 |

*C. Papadopoulos and A. Vivoli*

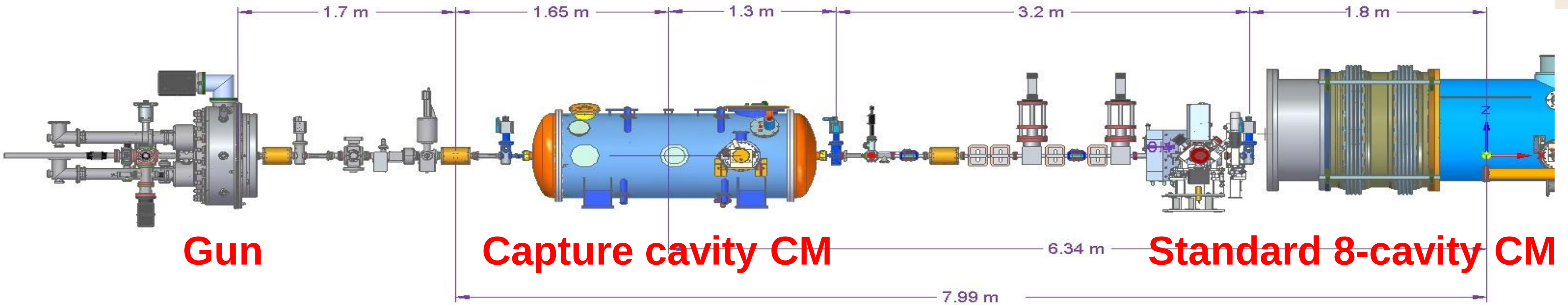
# Layout/Couplers performance (300pC)




*LBNL & A.Vivoli/FNAL*



# Layout 2 Advantages (not in baseline)

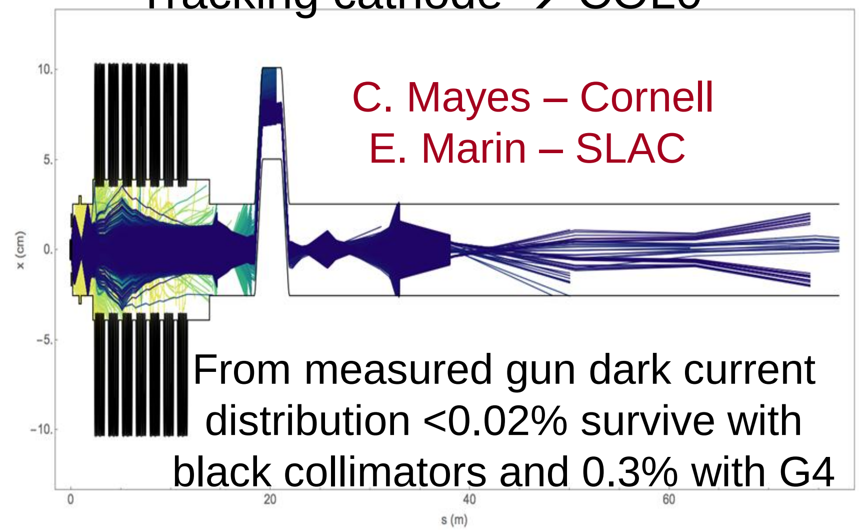



- Improved beam quality, can work at low energy injection (350-750keV)
- Modest cost increase over Layout 1
- Accommodate essential diagnostics at 10 MeV energy
- Operational flexibility:
  - Easier to replace the capture cavity CM
  - Have good e-beam quality if 1$^{st}$ cavity of the 8-cavity CM fails
- Preferred for early commissioning with limited cryoplant
- Layout 1 optimization forces 2$^{nd}$ and 3$^{rd}$ cavity gradient <3 MV/m

# Collimation Studies

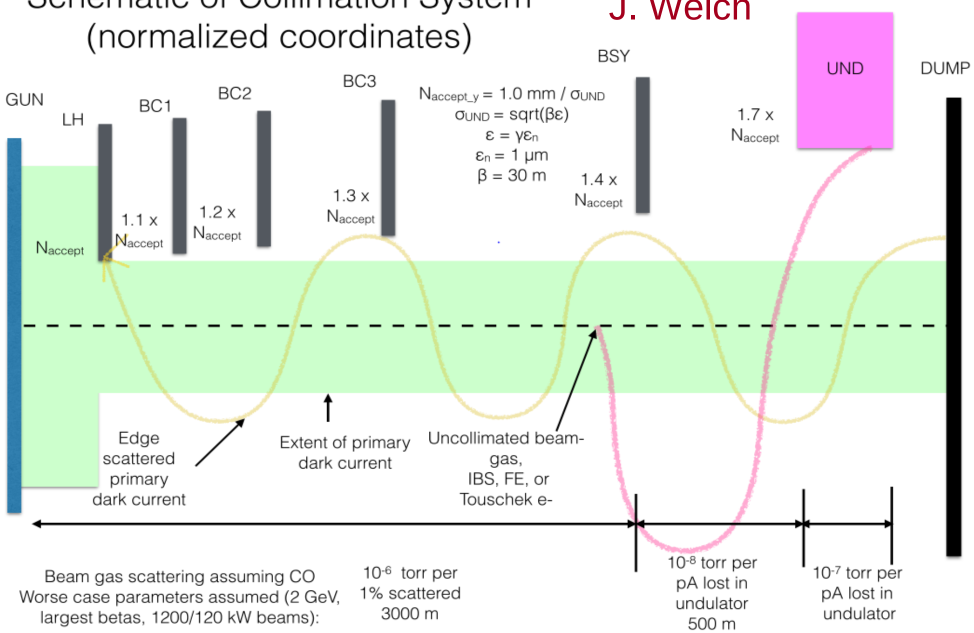
- Linac designed for 1.2 MW electron beam power but undulator dumps designed to 120 kW
- Controlling beam halo and losses important throughout
- Four or five stages of (x, x’, y, y’, DE) collimation
- Could add Dt collimation in Bypass and COL0

Tracking cathode → COL0



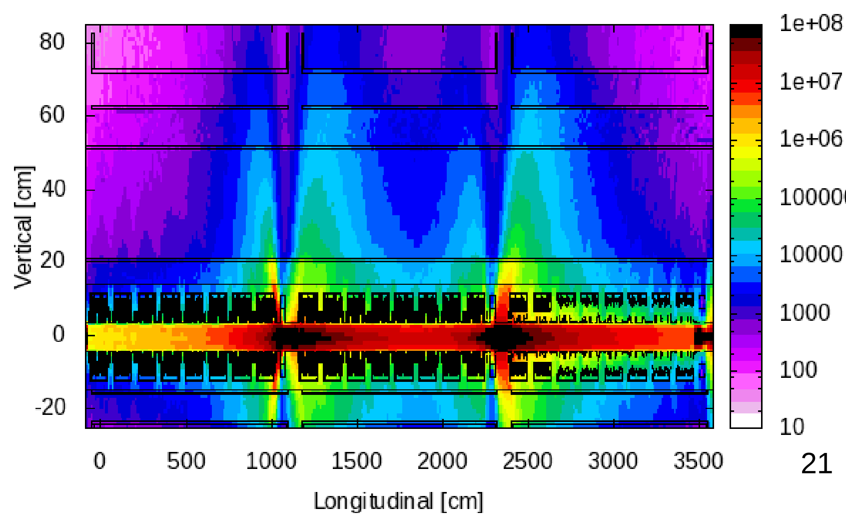

Schematic of Collimation System (normalized coordinates)

J. Welch

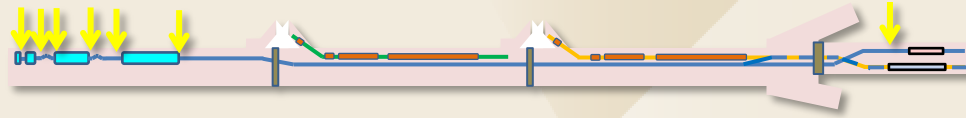



N.Solyak, FNAL meetiing, March10, 2015

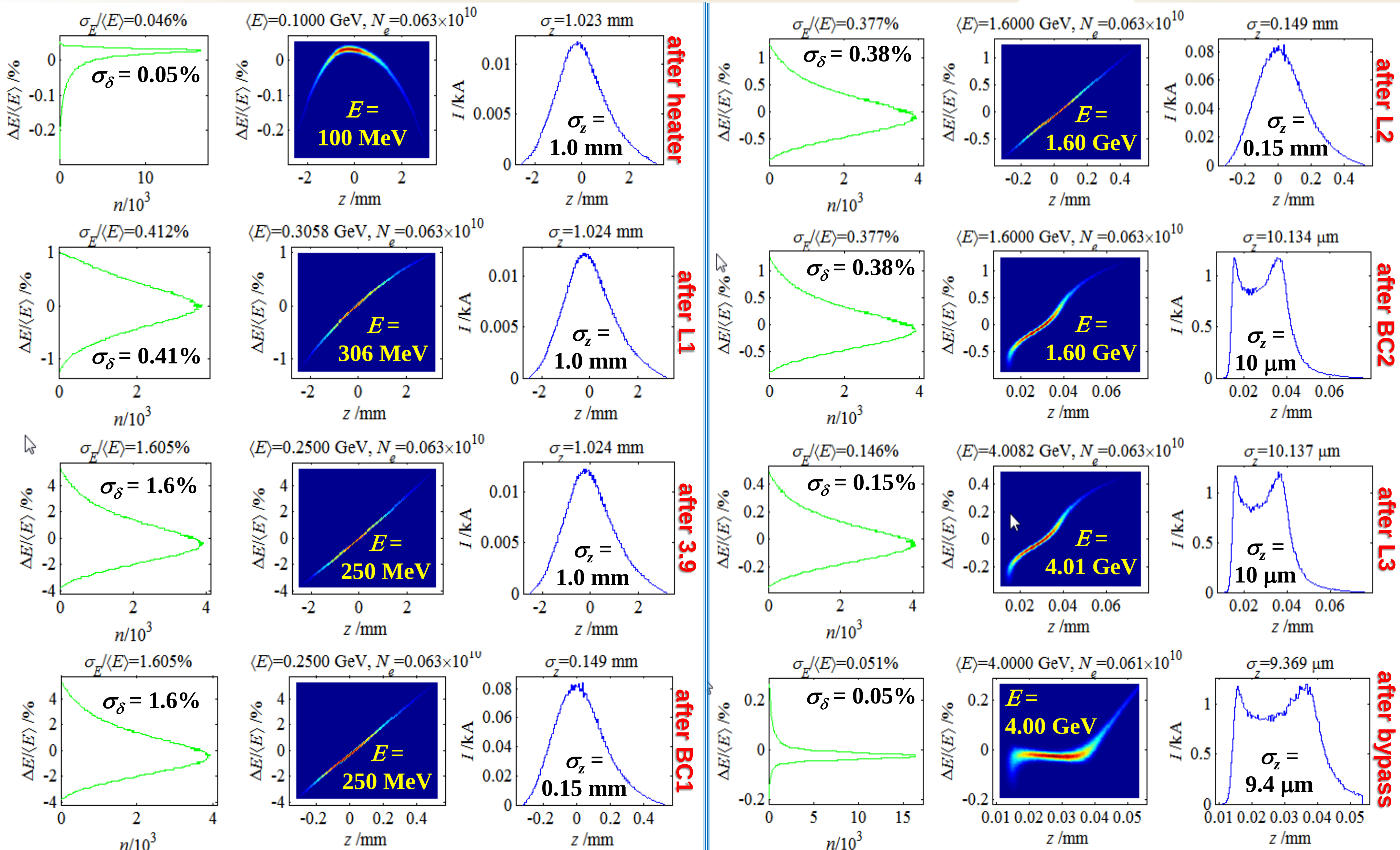
FE Simulation: Z. Li, C. Xu, L. Ge, M. Santana



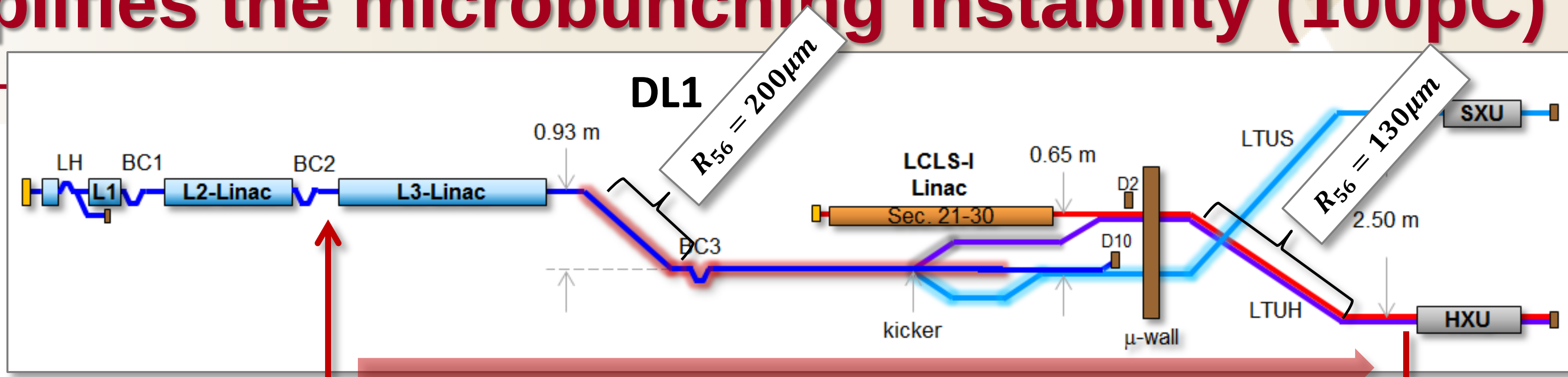
See PRD: *LCLSII-2.4-PR-0039, 0040, 0110*



# Bunch Compression at 100 pC (2D Tracking in *LiTrack*)

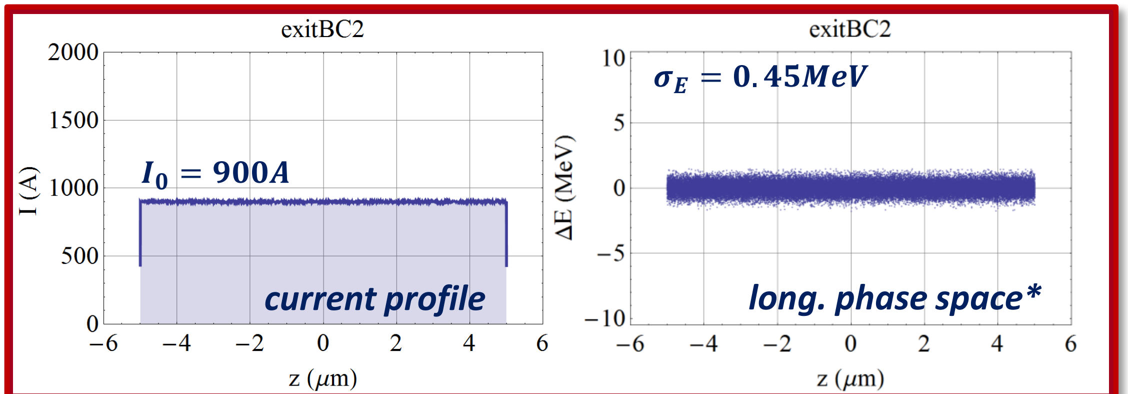


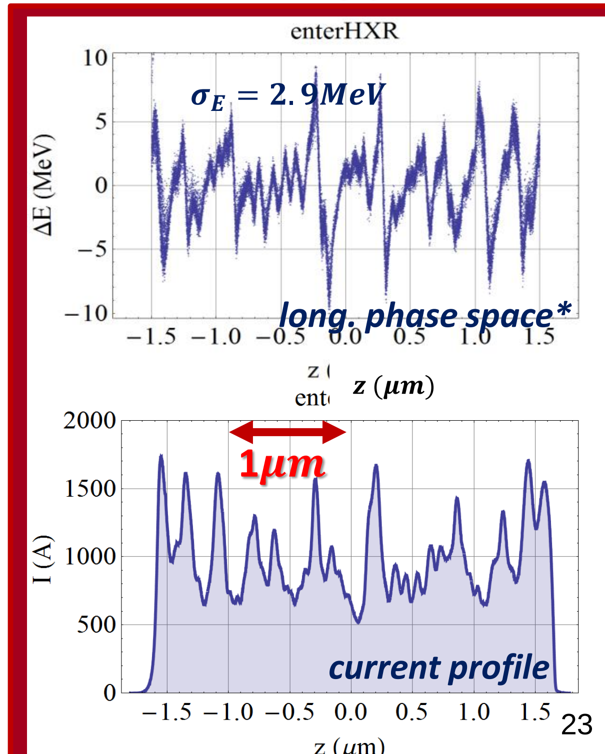
# Transport through doglegs/bypass greatly amplifies the microbunching instability (100pC)




**Start simulation with smooth beam model at exit of BC2**

**Beam as observed at HXU FEL is strongly microbunched**




- Macroparticle simulation of **flat-top** model beam with **gaussian** uncorrelated energy spread at exit of BC2
  - represents short section of $Q = 100pC$ bunch (laser heater on.)

M. Venturini, J. Qiang (***LBNL***)

- Microbunching on **sub-$\mu m$ scale** develops through DL1 (entrance of bypass) and transport section between $\mu$-wall and FEL

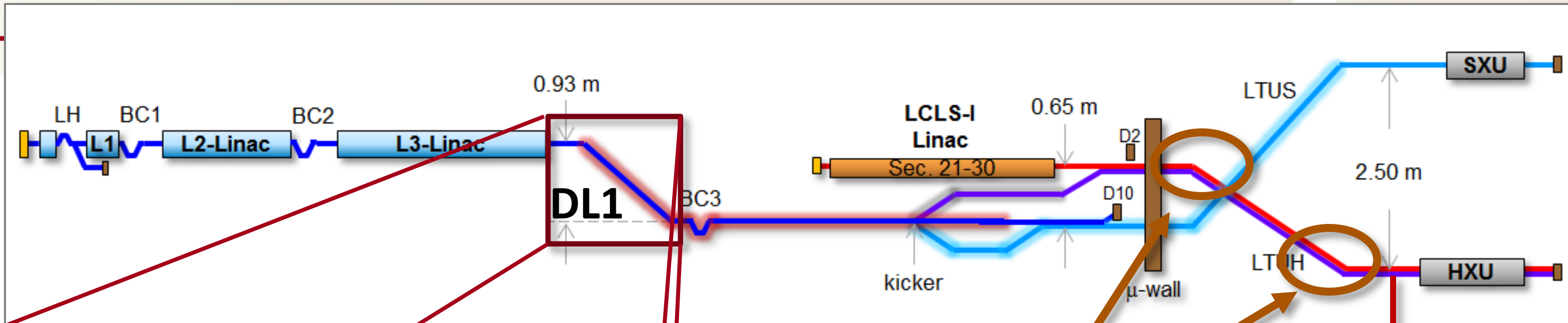


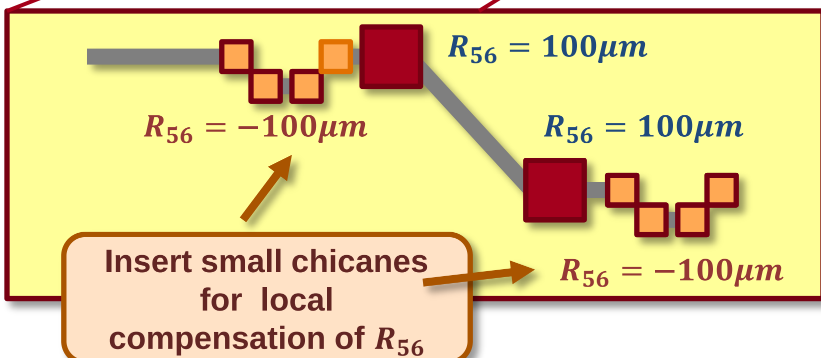


** Correlated energy chirp removed*

# A solution:

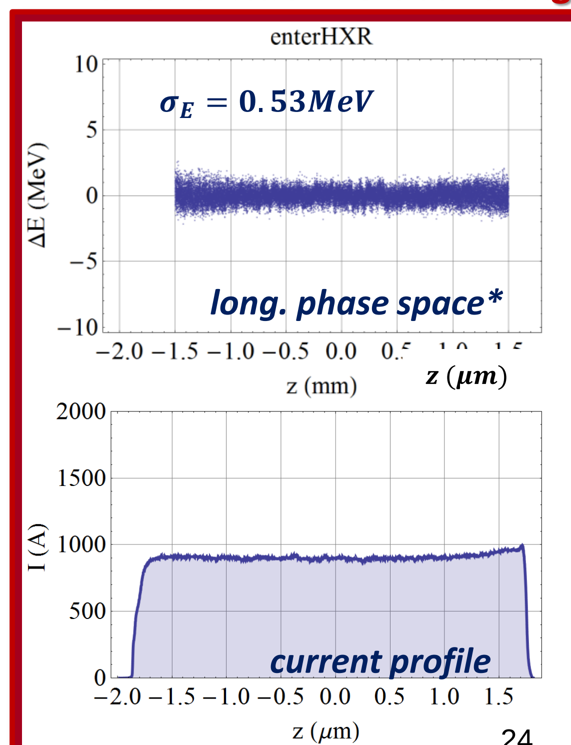
## Make all main doglegs locally isochronous




Insert small chicanes for local compensation of $R_{56}$ here as well

**Beam as observed at HXU FEL shows little microbunching**




- Non-local compensation of $R_{56}$ not as effective.
- Alternate local compensation schemes may be possible
- Robustness against jitters, errors?
- Delaying compression to exit of bypass is also a way to reduce microbunching

** Correlated energy chirp removed*

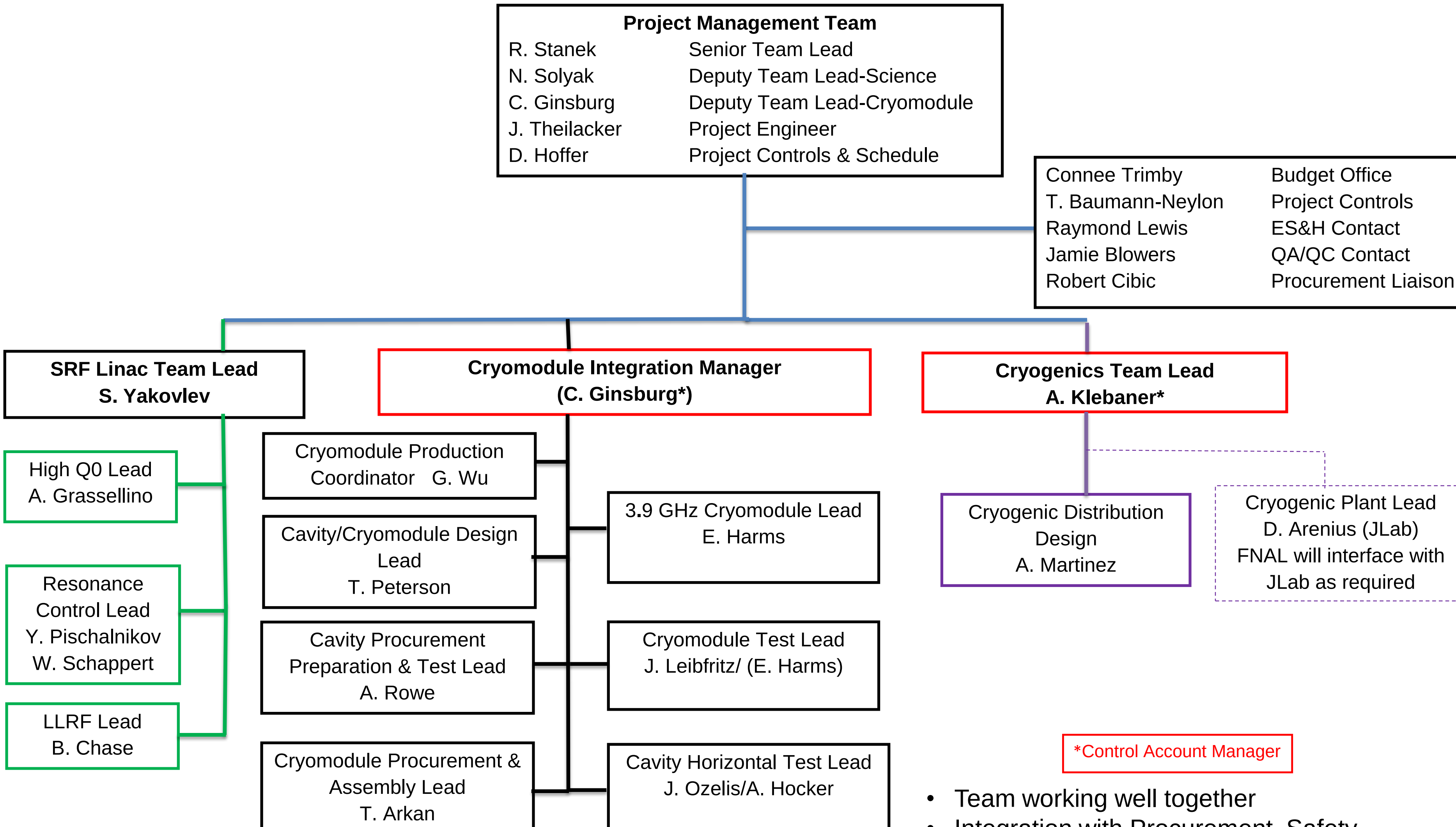
M. Venturini, J. Qiang (***LBNL***)

# FNAL's scope of work for LCLS II

**JLAB and FNAL are responsible for SCRF linac 35 CM's ~ 50% / 50%**

- Work on High Q0 development (FNAL led effort on N-doping)
  - Goal is to establish that the parameter choice of 2.7e10@16MV/m (in production) is valid, and that the cryoplant design capacity is correct
- Design, fabricate & test **seventeen 1.3 GHz cryomodules**
  - 8 cavities and one SC magnet/BPM per cryomodule (CW)
  - Current baseline includes cold/RF testing of half of the CM
    - Extent of testing can be adjusted based on initial results
- Design, fabricate & test **two 3.9 GHz cryomodules**
  - 16 cavities total (based on 1.3 GHz design)
- Design & fabricate **cryogenic distribution system**
  - Interfaces with cryomodules, cryoplant and SLAC tunnel
- For above deliverables provide installation and commissioning support at SLAC
- Assistance with linac accelerator physics and LLRF control

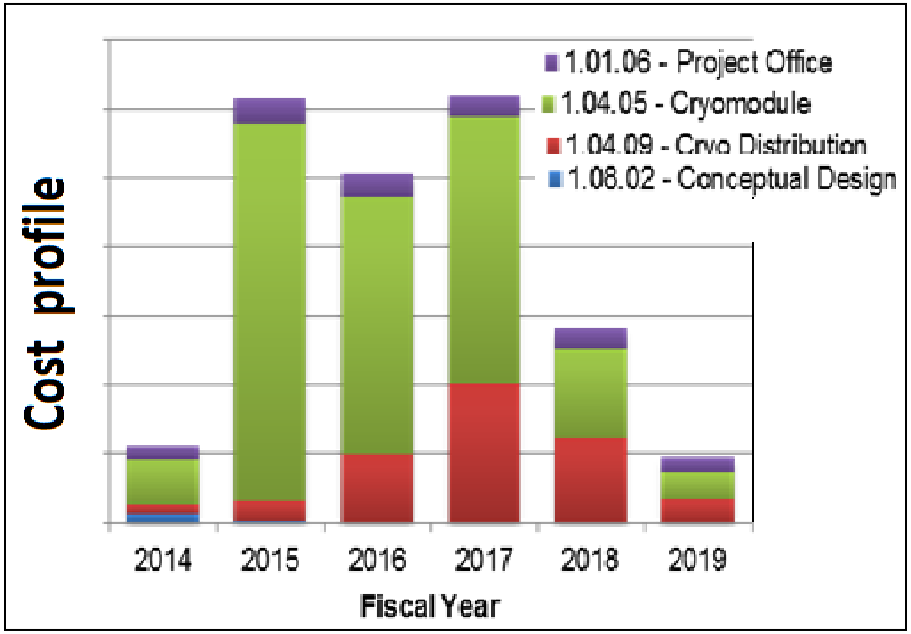
# FNAL Organization Chart

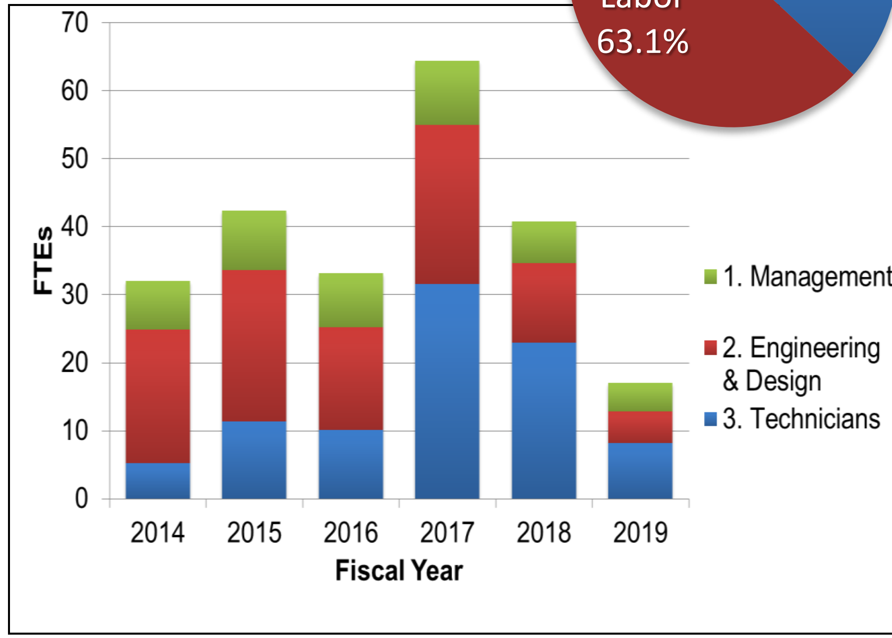


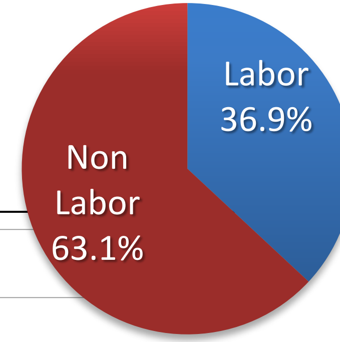

*Control Account Manager

- Team working well together
- Integration with Procurement, Safety, and QC is developing well

# Cost Data - FNAL




- Procurements dominate in FY15 and FY16
- Production CM assembly & test starts in FY16 ends in FY19 (1.3 GHz first then 3.9 GHz)
- Cryo Distribution System will use a build to spec methodology

| FNAL | |
|---|---|
| Labor | $41,799 |
| Non Labor | $71,368 |
| **Total** | **$113,168** |

*- Values in $K*

# FY15 Activities

- Finalize the High Q0 R&D and arrive at a target value
- Complete the 1.3 GHz CM design in first part of FY15
  - Prototype and Production designs are almost identical
  - Design verification program to prove a design (complete by Aug.2015)
- Major procurements
  - Nb and Nb/Ti material for Production cavities
    - RFP have closed and the evaluation phase complete
    - Place the orders at the end of Oct 2014
  - Components for Prototype CM **(cavities exist – receive High Q0 treatment)**
    - Final Design Review in Jan 2015
    - Start assembly of Prototype CM in Jun 2015
  - Components for Production CM
    - Order components for cold mass and vacuum vessel Jun 2015
- Complete final reference designs on Cryo Distribution System
    - Surface and Tunnel components Jul 2015

# Cryogenic and Cryomodule design work

# Cryogenic Systems: Scope & Schedule

***1.04.05: (Fermilab)***

- Superconducting RF 1.3 GHz Cryomodule Design, Production (50%), and Test
- SRF 3.9 GHz Cryomodule Design, Production and Test

***1.04.06: (Jefferson Lab)***

- Superconducting RF 1.3 GHz Cryomodule Production (50%) and Test

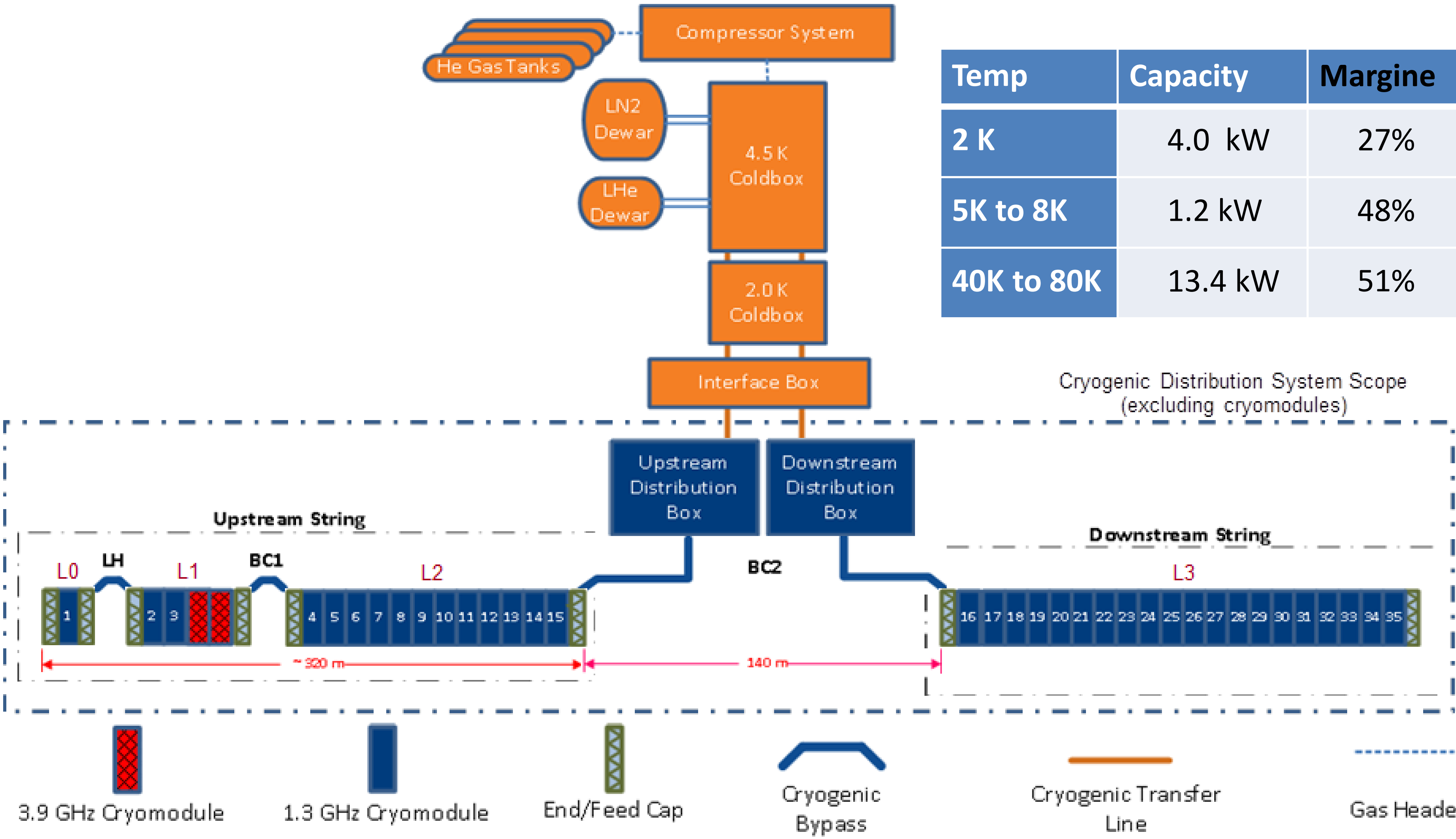
***1.04.08: (Jefferson Lab)***

- Cryoplant Design/Build Procurement → 4.5 K Cold-Box, 2.0K Cold-Box, Warm Helium Compressors, Auxiliaries

***1.04.09: (Fermilab)***

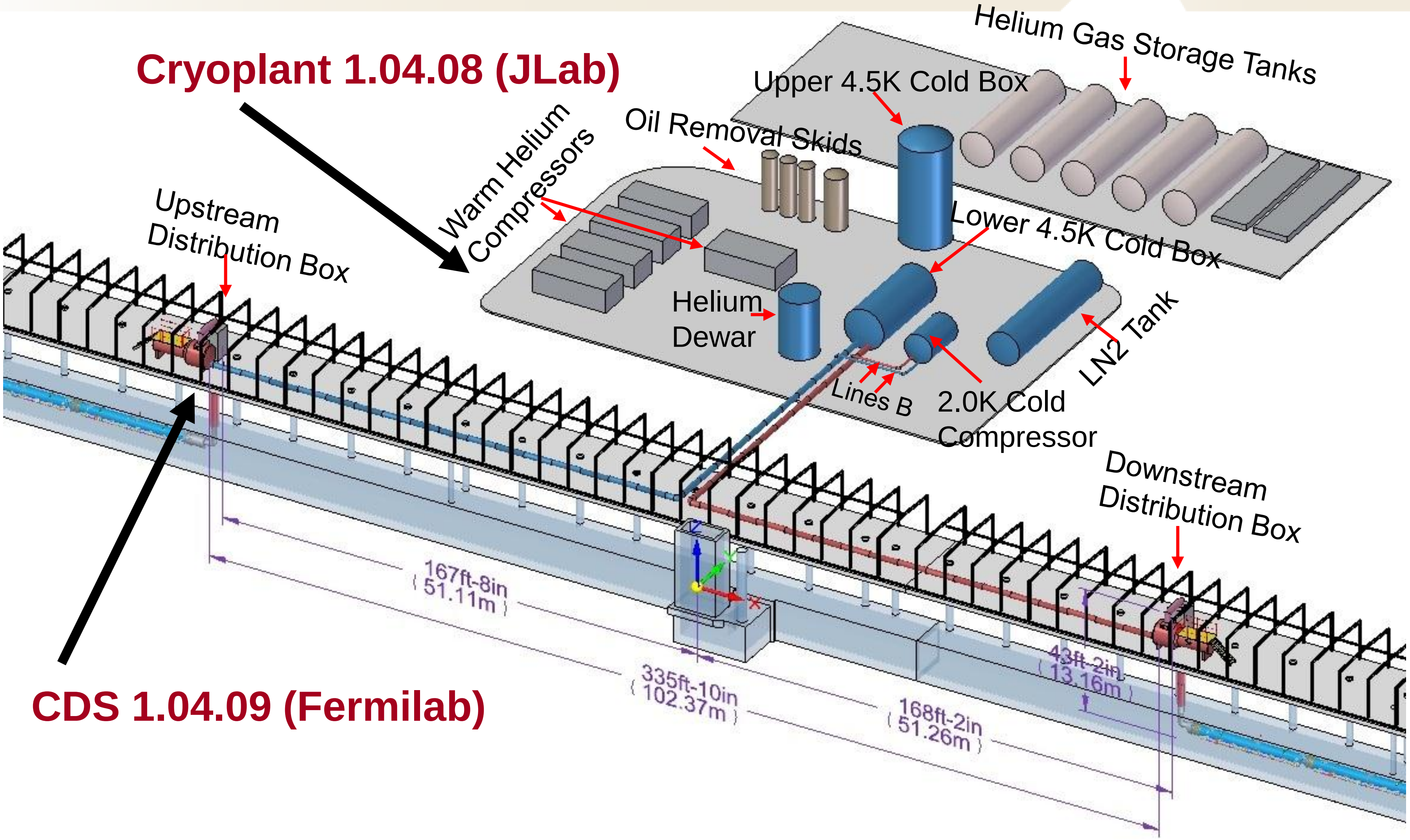
- Cryogenic Distribution System including master valve-boxes

# Baseline Cryogenic System




| Temp | Capacity | Margine |
|---|---|---|
| 2 K | 4.0 kW | 27% |
| 5K to 8K | 1.2 kW | 48% |
| 40K to 80K | 13.4 kW | 51% |

# Cryoplant Schematic showing Cryogenic Distribution System (CDS)



# Cryoplant Backup Options

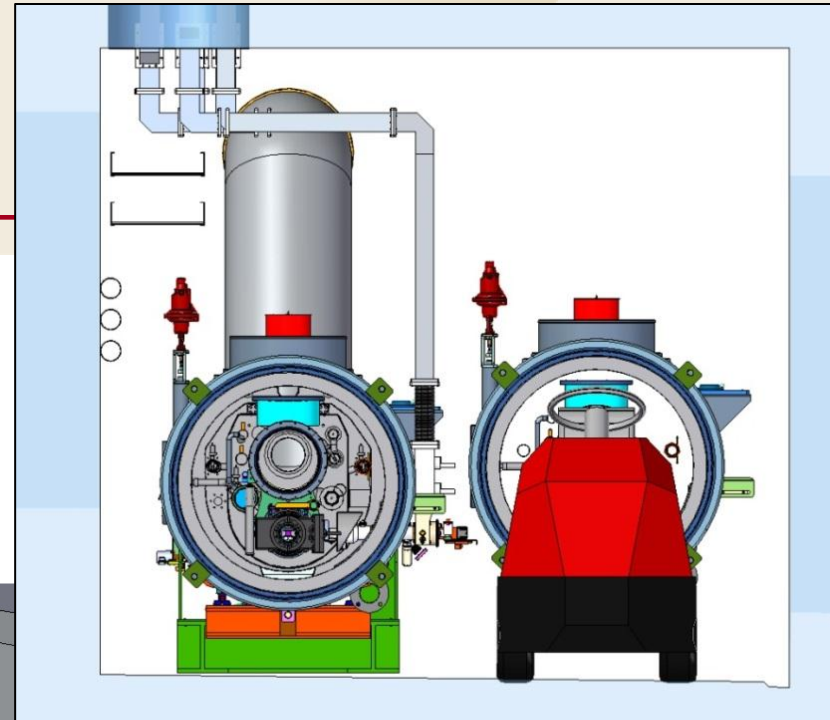
M. Ross

- Plan A: $Q_0$ >2.7e10
  - Baseline Cryoplant has capacity to support the design linac
  - If more capacity is needed, add an additional cryoplant
- Plan B: $Q_0$ >2.4e10
  - Install a separate 1.3kW 5K plant for shield cooling
  - Place in baseline building, sufficient power and water
- Plan C: $Q_0$ >2.0e10
  - Install a supplemental plant providing 1.5kW at 2K
  - Second building, additional power and water
  - Well suited to provide cryogens to the beginning of the Linac
- Plan D: $Q_0$ >1.5e10 → 2nd Cryoplant

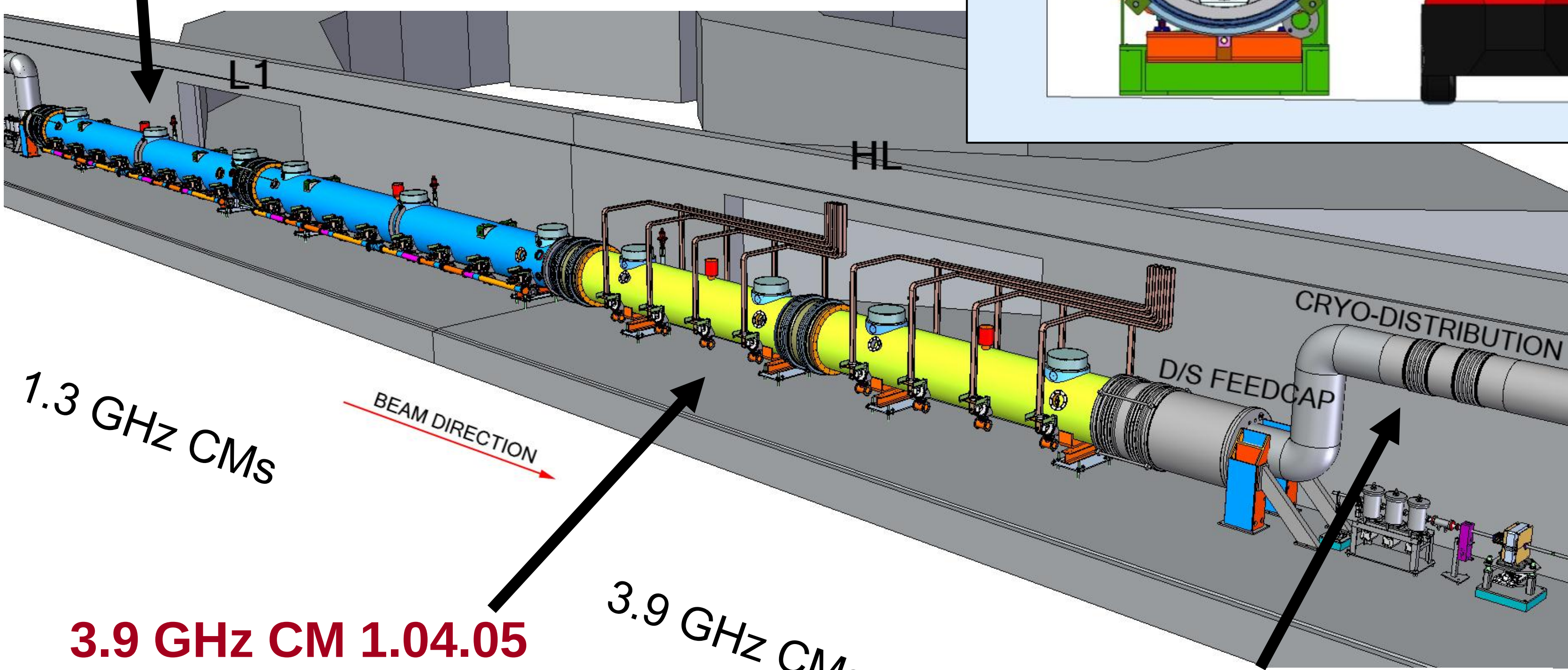
- *Trigger (1):* *Aug.2015* ← HT test results (8cav)
- *Trigger (2):* *May 2016* ← pCM test results (16 cav.)

- The baseline JLAB 4.5K cryoplant procurement is fully compatible with these options
- The accelerating cavity procurement is also compatible.
  - The cavity $Q_0$ sets the size of the plant needed

# Tunnel Layout and Cross-section



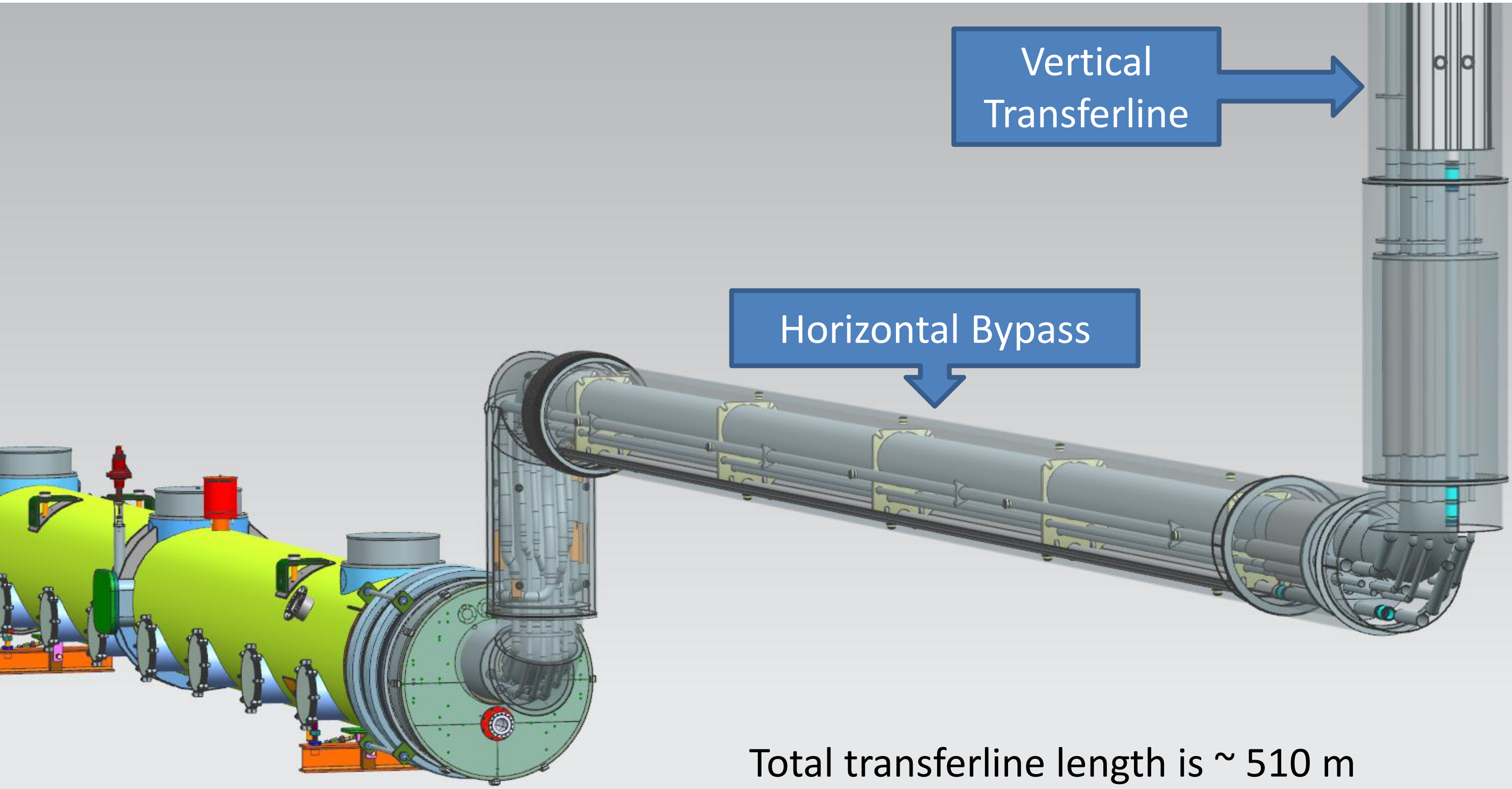
**1.3 GHz Modules 1.04.05/ 1.04.06 (Fermilab/JLab)**




**3.9 GHz CM 1.04.05 (Fermilab)**

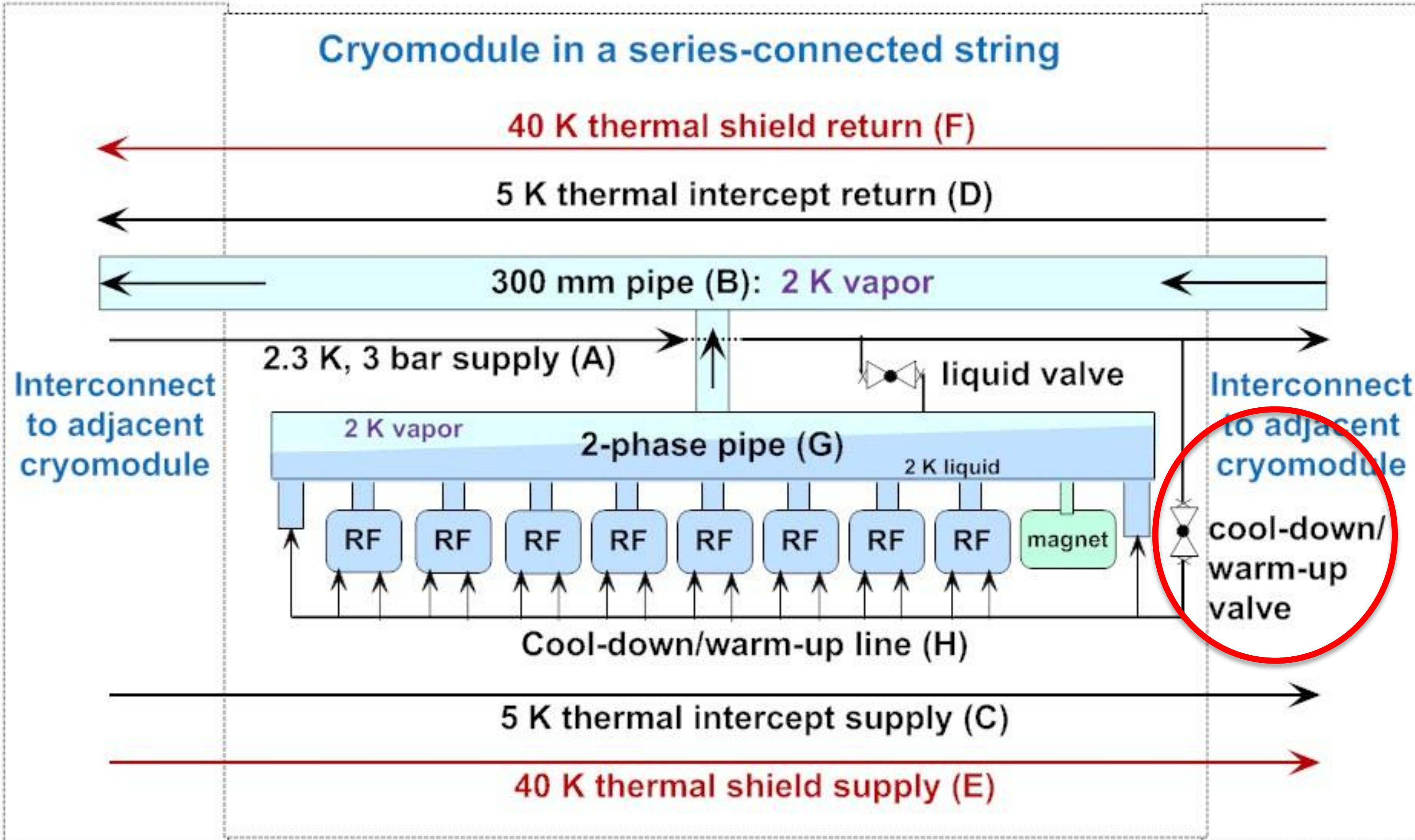
**CDS 1.04.09 (Fermilab)**

# CM, Feed Cap and Bypass and Vertical Transferline

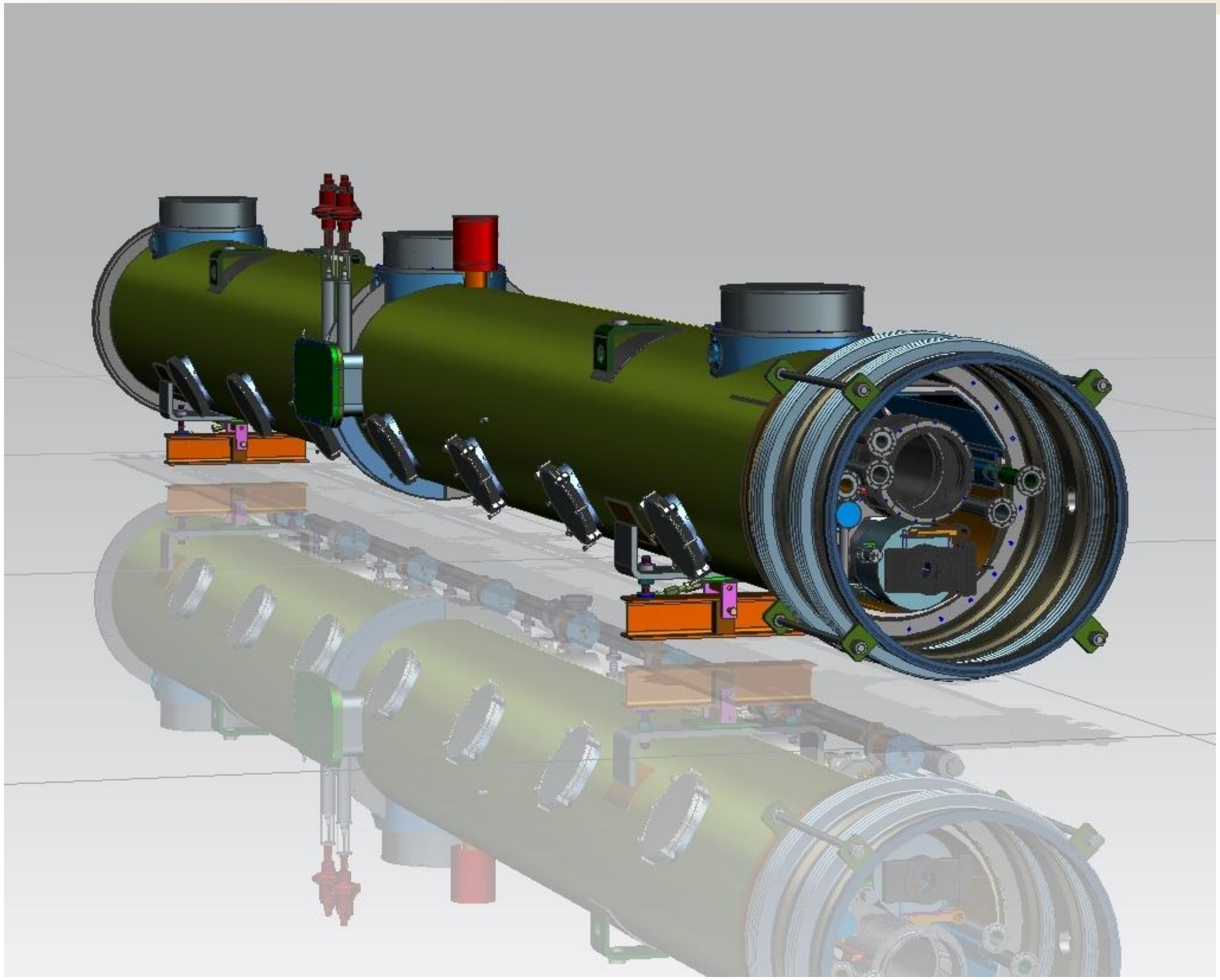



Total transferline length is ~ 510 m

# New -- modification for fast cool-down (cool-down valve on each cryomodule)

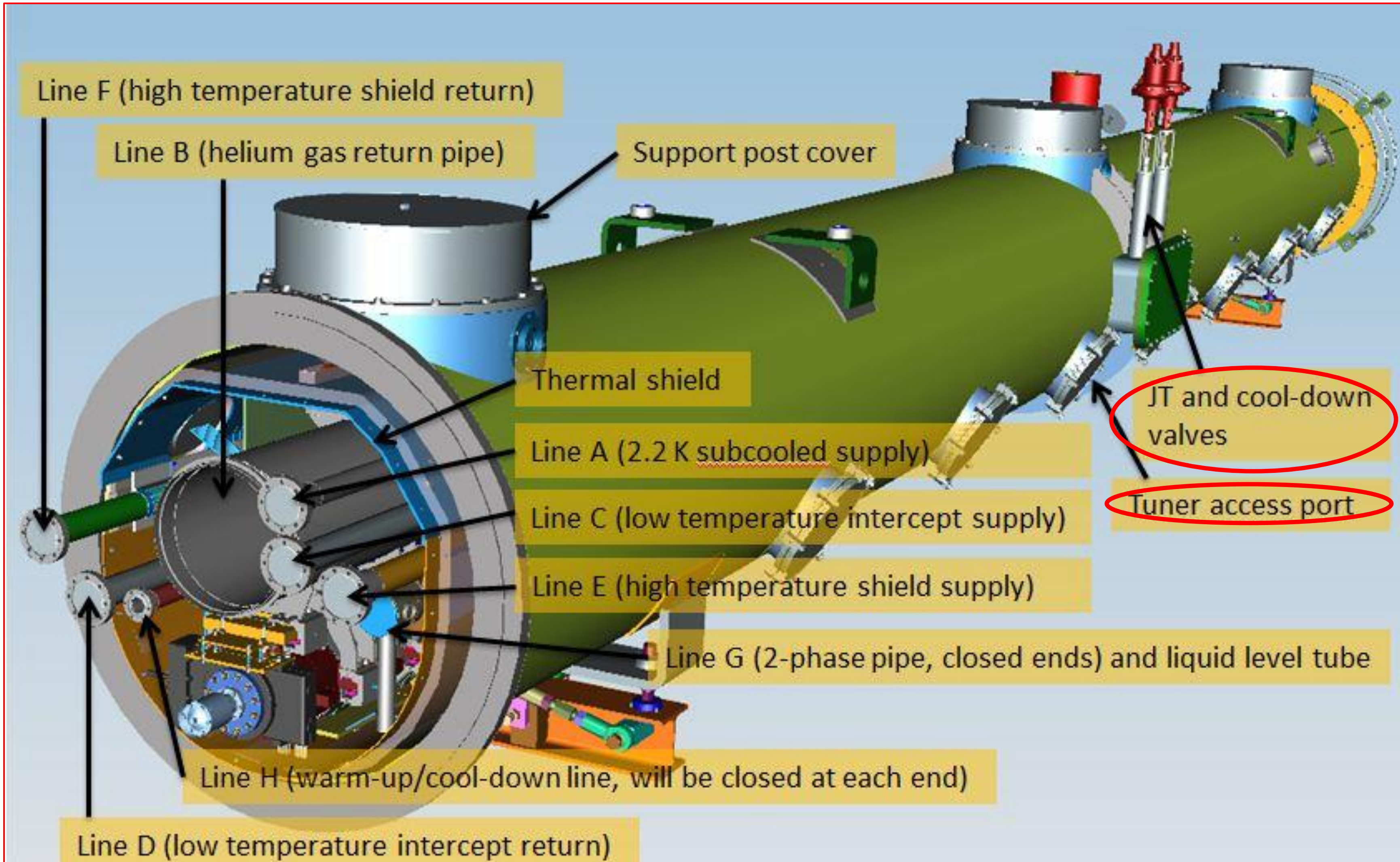


# CM in 3D - Design Maturity

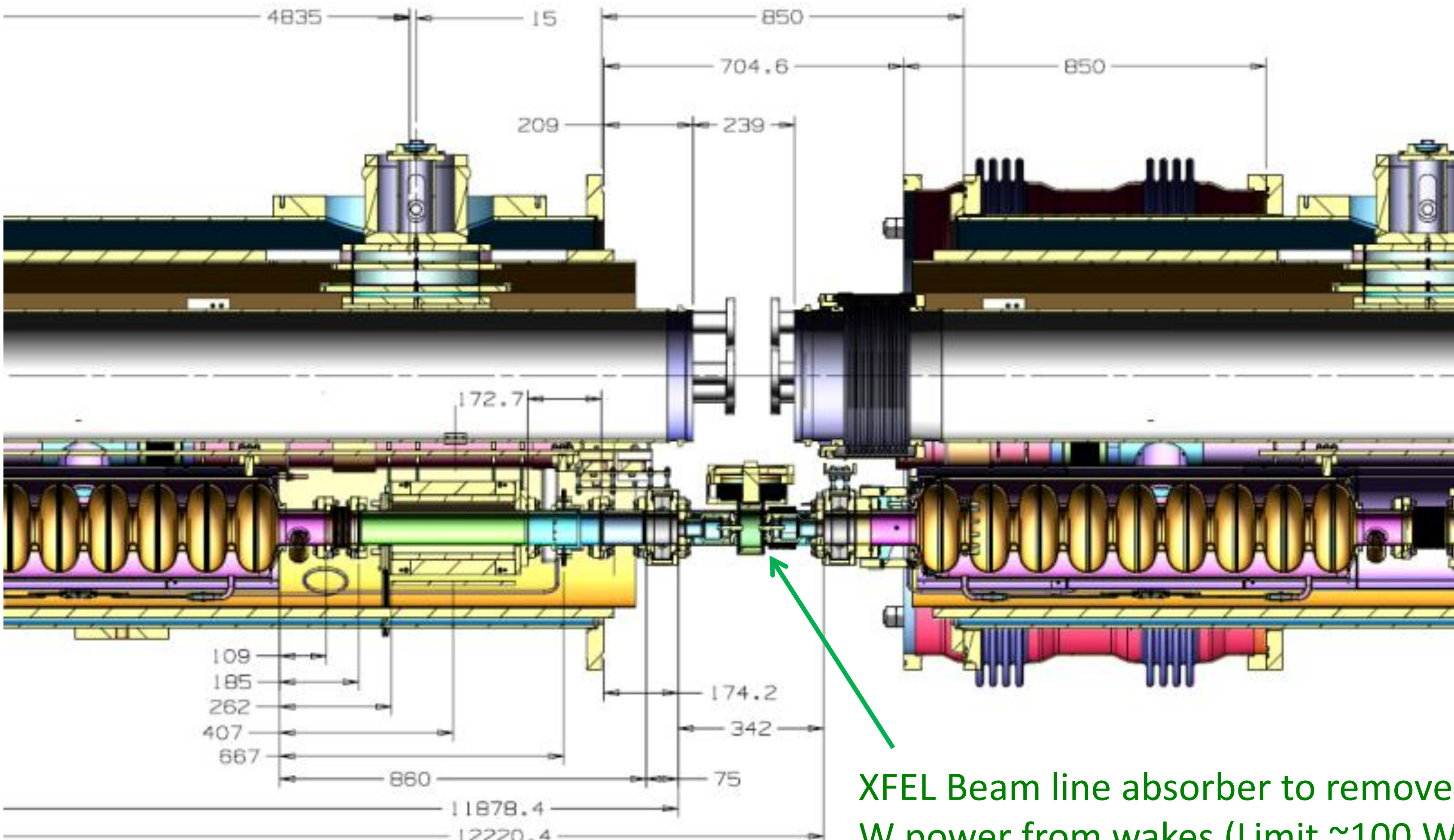


- XFEL/ILC like design
- Incorporating required changes to preserve High Q0 is already in progress
- Changes are not significant schedule drivers
- Once full technical specification is complete => will adjust cost estimate

# Cryomodule in 3D - Design Maturity



# 1.3 GHz Cryomodules Connection




XFEL Beam line absorber to remove ~20 W power from wakes (Limit ~100 W)

# ILC Type 3+ CM Modifications for LCLS-II (components)

Component design – leverage existing designs optimally

- Cavities – XFEL identical
- Helium vessel – XFEL-like (small modifications)
- HOM coupler – XFEL-like or identical
- Magnetic shielding – increased from XFEL/ILC to maintain high Q0
- Tuner – XFEL or XFEL-like end-lever style (FNAL design ?)
- Magnet – Fermilab/KEK design split quadrupole
- BPM – DESY button-style with modified feedthrough
- Coupler – XFEL-like (TTF3) modified for higher QL and 7 kW CW

Concerns based on global experience

- Tuner motor and piezo lifetime: Consider access ports
- Maintain high Q0 by minimizing flux trapping: possible constraints on cooldown rate through transition temperature

**Functional Requirements Document: "1.3 GHz Superconducting RF Cryomodule," LCLSII-4.5-FR-0053-R0, 6/23/2014 Original Release.**

# ILC Type 3+ CM Modifications for LCLS-II (cryo-mech)

Cryo-mechanical design – increased pipe sizes

- Larger chimney pipe from helium vessel to 2-phase pipe
- Larger 2-phase pipe (~100 mm OD) for low velocity vapor flow

Both high heat load & 0.5% slope of the SLAC tunnel require

- Closed-ended 2-phase pipe (line G) providing separate 2 K liquid levels in each cryomodule
- 2 K JT (liquid supply) valve on each cryomodule

For fast cool-down, cool one cryomodule at a time

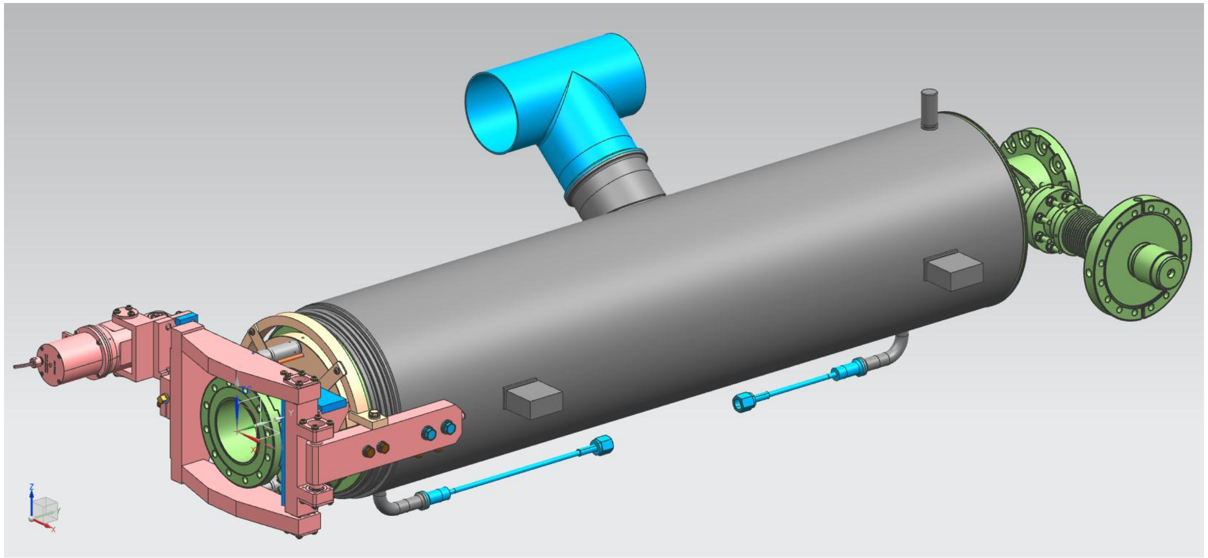
- Closed-ended warm-up/cool-down manifold (line H)
- Cool-down/warm-up valve on each cryomodule

Cost savings: Omit 5 K thermal shield

- Retain 5 K intercepts on input coupler

# Helium vessel

- Increased chimney for higher power - symmetrical
- Transition to SS for two-phase pipe
- Two LHe supplies
- Large diam bellow

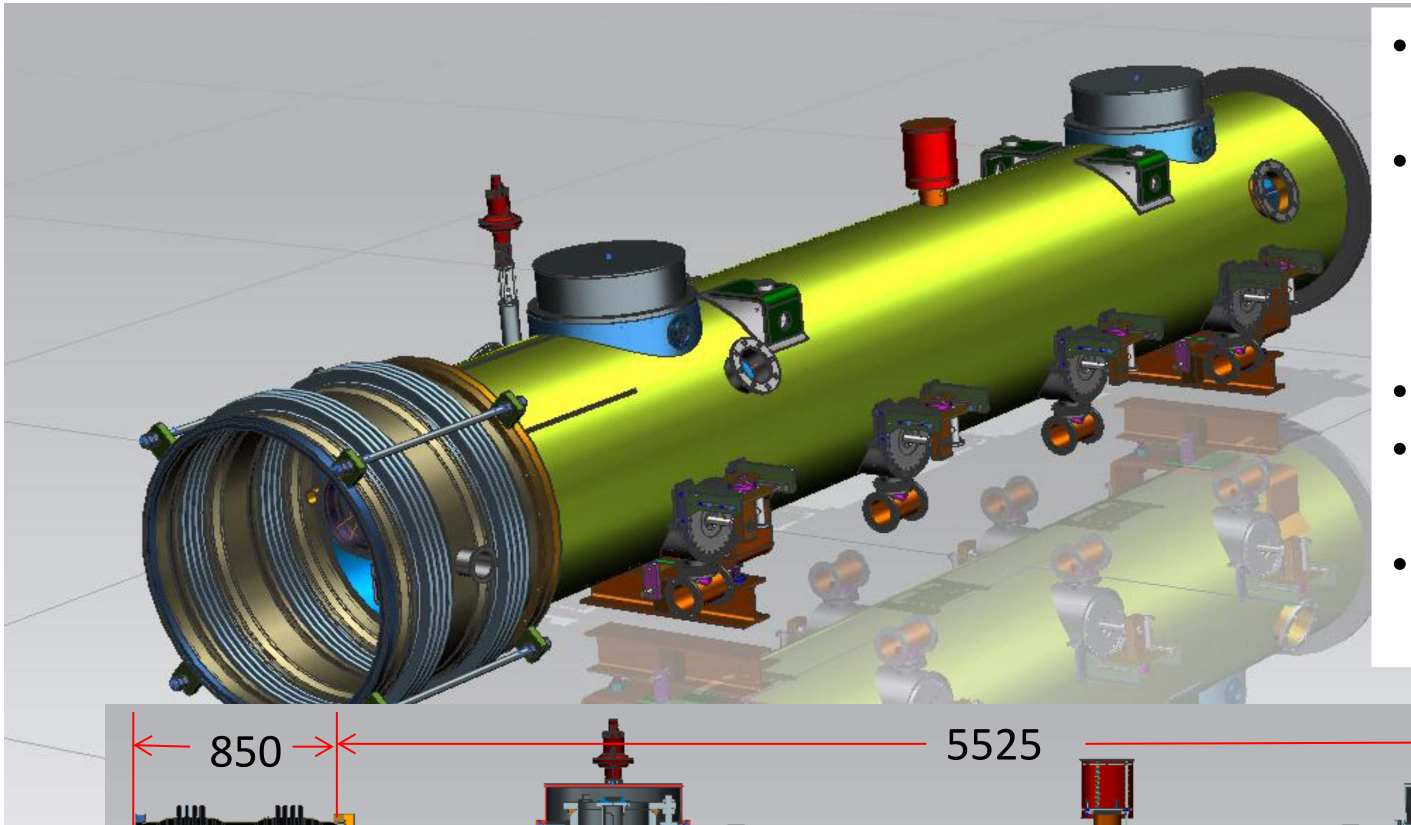


# 3.9 GHz CM DESY/FLASH experience

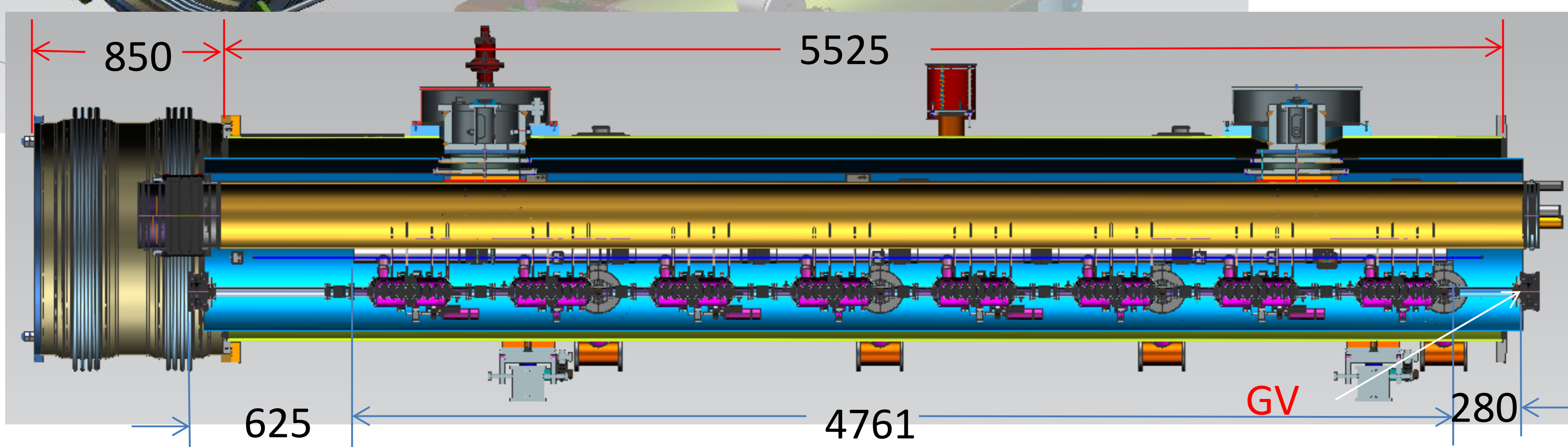
FNAL designed and built 4-cavity 3.9 GHz pulsed-operation linearizer CM, installed at DESY/FLASH

- Many years in operation
- Cavities routinely operate (pulsed) at ~20 MV/m

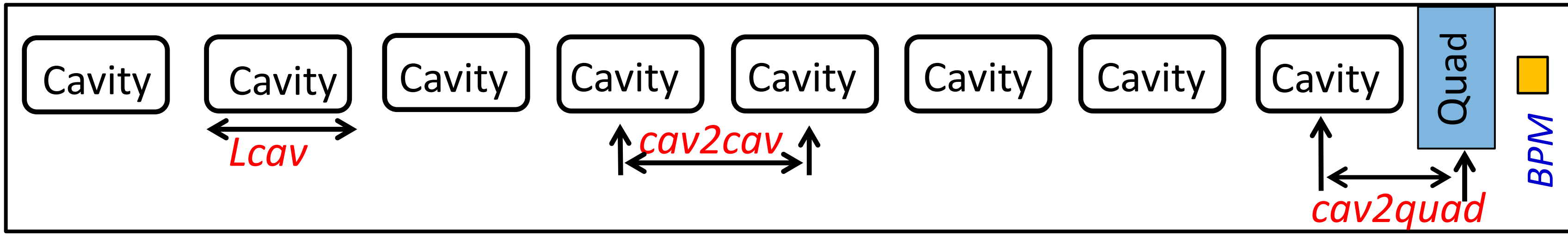
# LCLS-II 3.9GHz Cryomodule



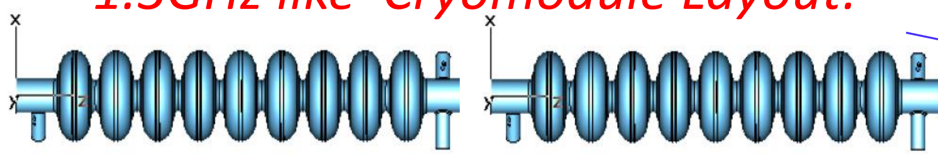
- Eight-3.9GHz Cavities (vs.4cav inFNAL/FL ASH)
- Power couplers from both sides (z-rotation to compensate coupler kick)
- 2-coldmass supports
- Interconnection bellows (not sliding)
- 38” OD vacuum vessel pipe (same as 1.3GHz)



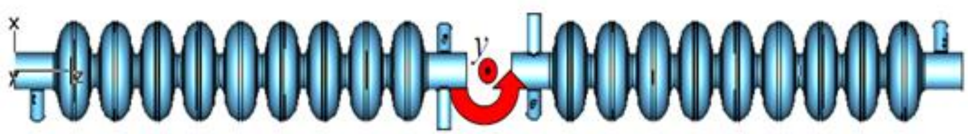
# 3.9 GHz Cryomodule Options



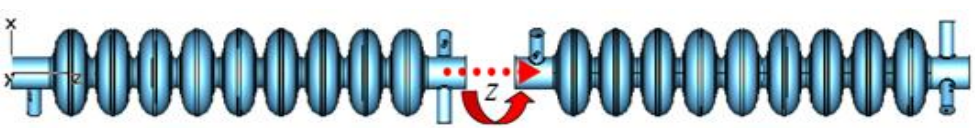

*1.3GHz like Cryomodule Layout:*

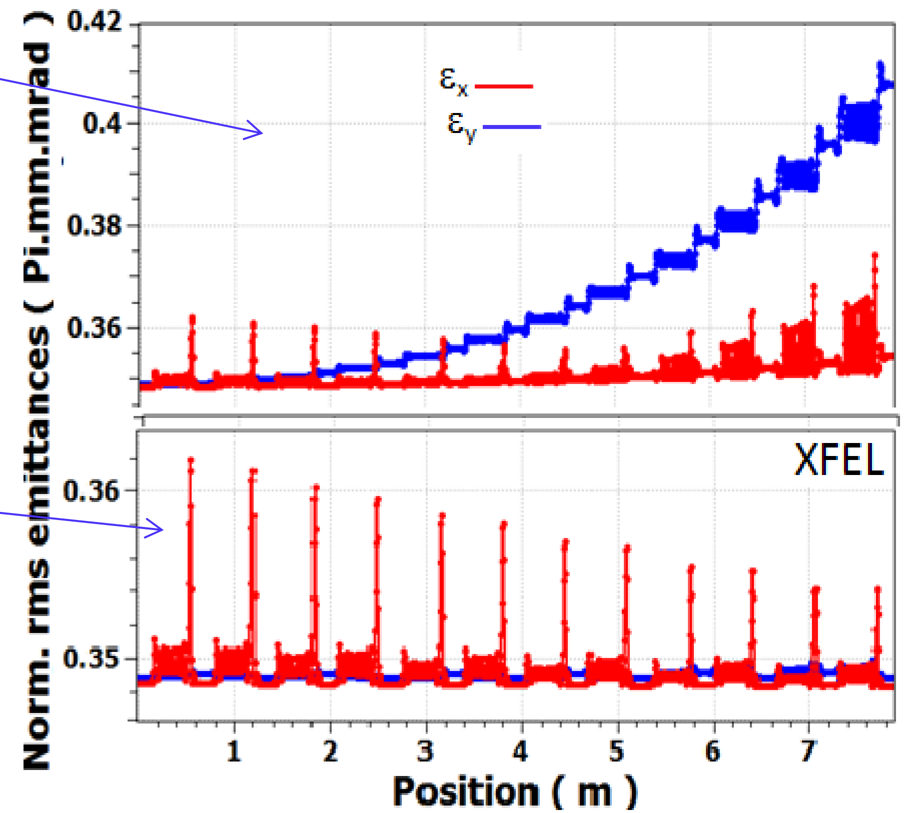


*FLASH Cryomodule Layout $y_{rot}$=180°:*



*XFEL Cryomodule Layout: $z_{rot}$=180°:*






Conclusion:

# 3.9 GHz CM Functional Requirements

- Less developed than 1.3 GHz CM; needed later
- Based on FNAL DESY/FLASH design and LASA Milan XFEL design
- Two eight-cavity CM's
- Cavity nominal operation $E_{acc}$ = 11.7 MV/m at $<Q_0>$=2.5E9 (8.8 W/cavity )
- Same vacuum vessel diameter as for 1.3 GHz CM's: similar cryogen transport cross section, thermal shielding, interconnect & cooling scheme
- Rotate every other cavity 180 degrees about beam axis to minimize RF coupler kicks; power couplers will extend out both sides of the CM
- No magnets; no BPM's

**Physics Requirements Document: "SCRF 3.9 GHz Cryomodule,"**
**LCLSII-4.1-PR-0097-R0, 6/23/2014 Original Release.**
**Functional Requirements Document: "SCRF 3.9 GHz Cryomodule," in preparation**

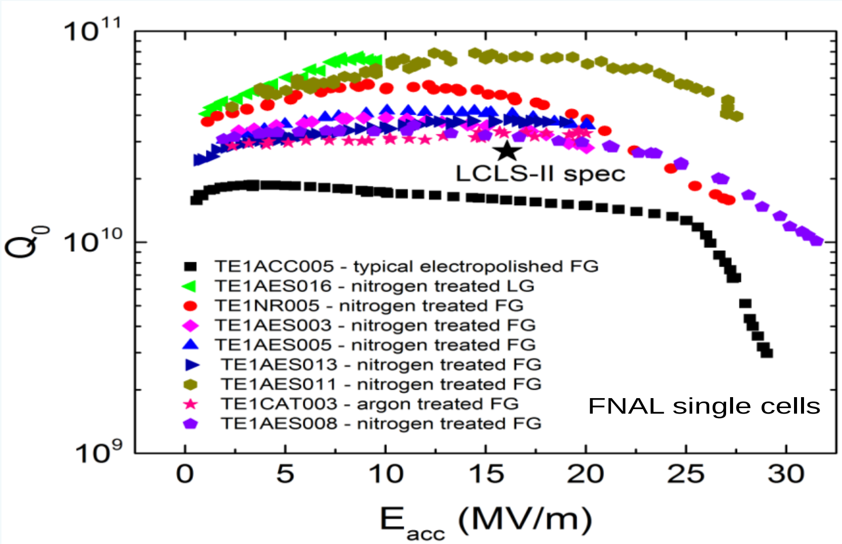
## High Q0 R&D program

# High Q cavity R&D (N2-doped) for LCLS-II project

- Allow to reduce total cryogenic loads to < 4kW / linac, provided by 1 cryo-plant (JLAB like design – 50M$ scale)
- Requirements: **Q0>2.7e10 @ 2K and $E_{acc}$=16MV/m**. (acceptance test > 18MV/m)
- Ambient magnetic field < 5 mGauss (tighter than in ILC and XFEL)
- Fast cooling of the cavity is a requirements → design of the CM
- Need studies at horizontal cryostat to optimize configuration of the cavity dressing and cool-down regime (Design Verification)
  - FNAL/HTS, Cornell/HTC;  JLAB/HTB.

# FNAL/Cornell/JLAB summary of single-cell results

- **FNAL** has completed **50+ single cell** tests
- Studied Q and quench as function of EP post bake (1-30 um)
- At least 5 different robust recipes demonstrated (vac.bake +$N_2$(time/press) + removal/um)
- Chose **recipe 1:** “6min-$N_2$ @25 mTorr” for 9-cell, 5-20 um EP

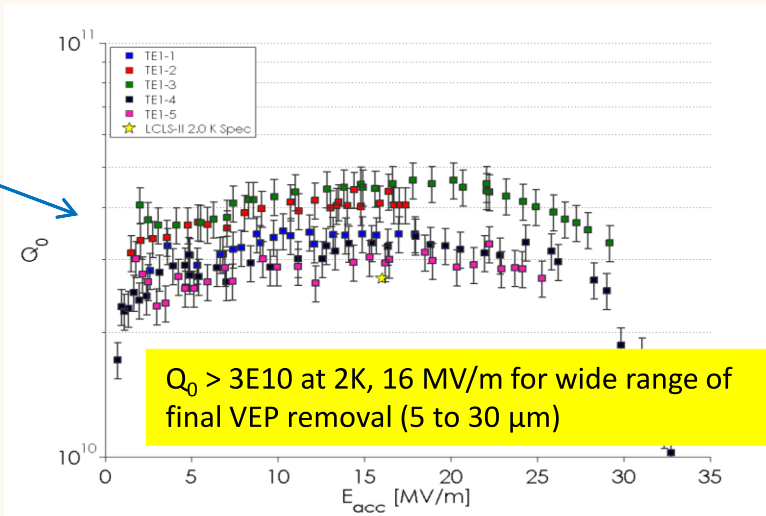



**Cornell – 5** Single-Cell 2.0K Results

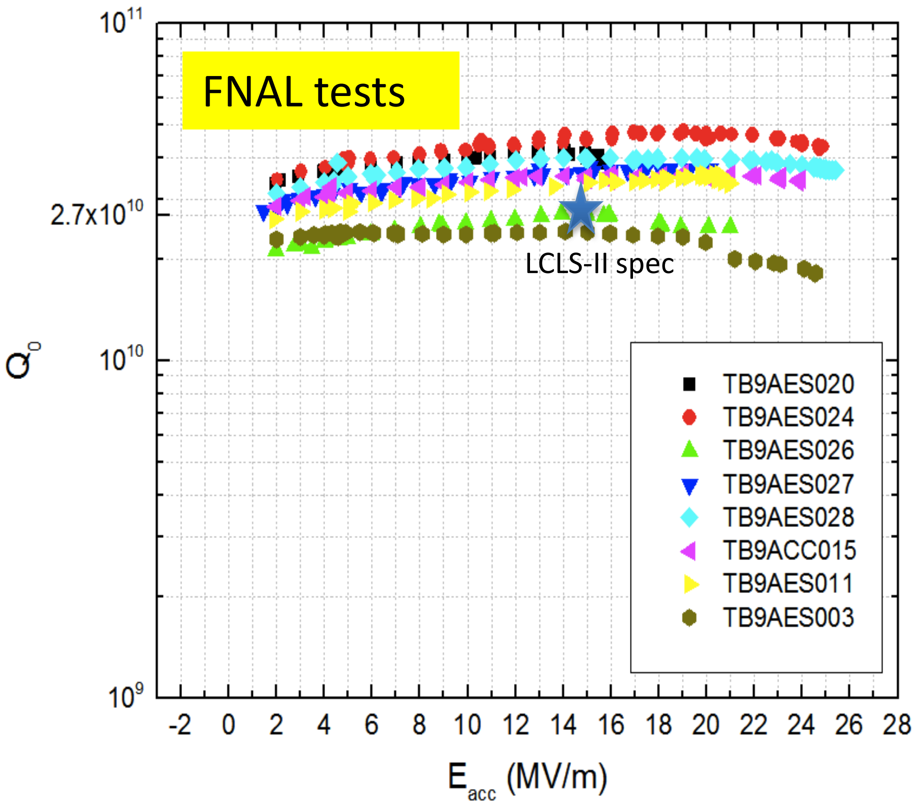
- Receipt 2: 100 um bulk VEP, 20min 40 mTorr $N_2$ @800C, 30 min vacuum anneal, final VEP(5-30um)

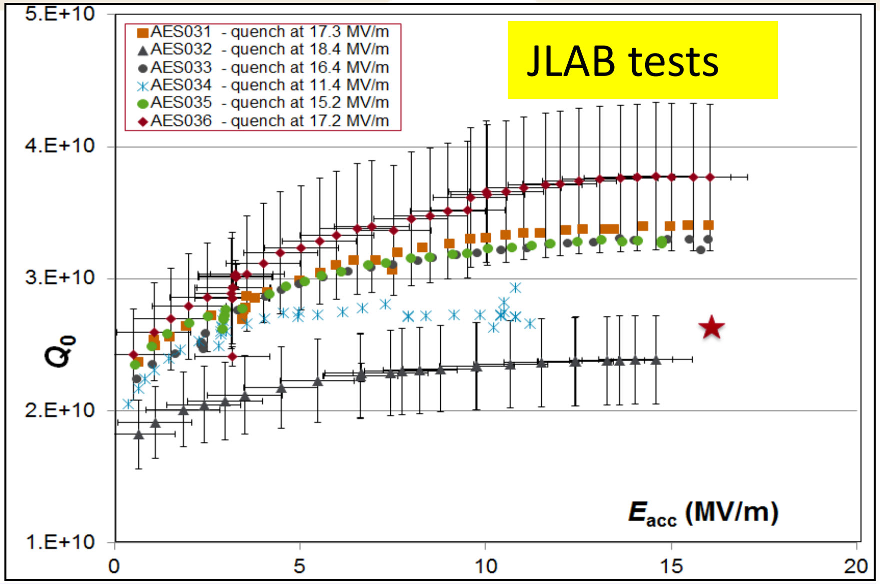
**JLAB – 9** Single-Cell 2.0K Results

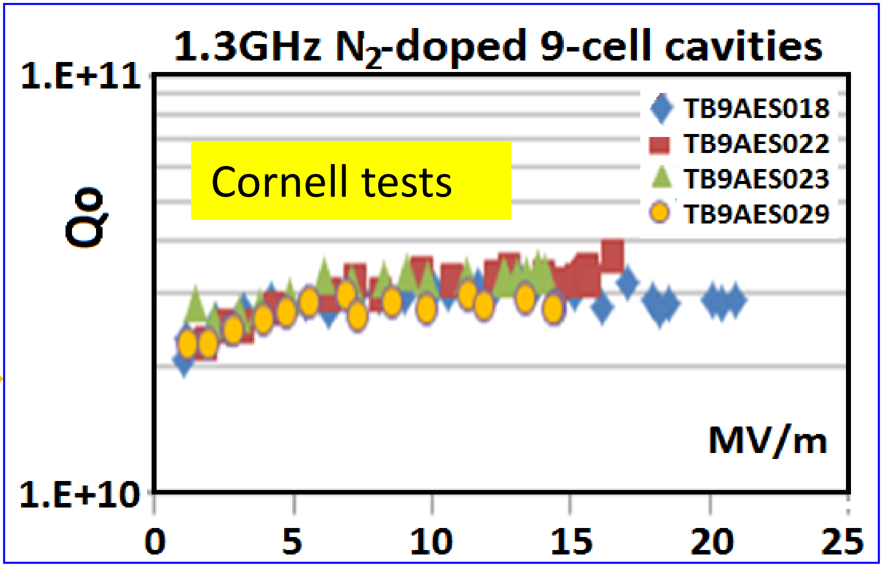
- Receipt 2: 20min 30 mTorr $N_2$ @800C, 30 min vacuum anneal, final VEP(5-30um)



# All nine-cell 2K results – one CM milestone (undressed in VTS)

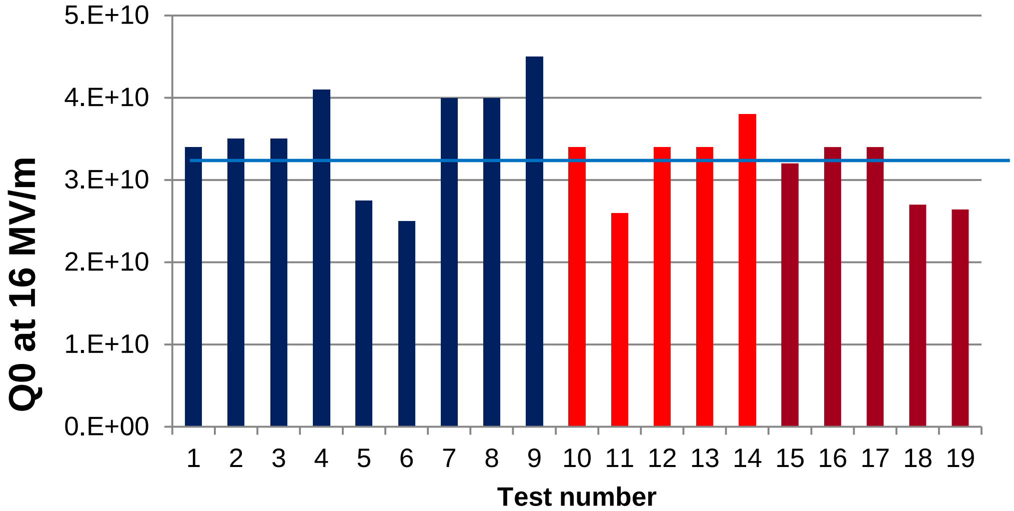



- recipe 2:100 um bulk VEP, 20min N2 @800C, 30 min anneal, final VEP
- $Q_0$ > 3E10 at 2K, at 16MV/m (or max field reached) for all nine cells
- Quench fields of 14 to 22 MV/m

# Nine-Cell VTA Test Results (19 each)



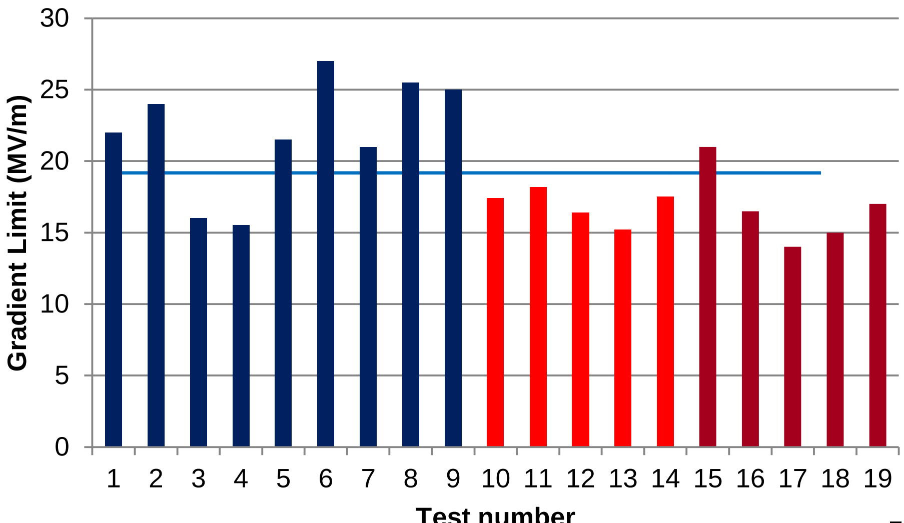

Q0 – Average 3.4e10

***Q0 (CM) ~ 0.8 Q0 (VTA) ~ 2.8e10***

2 cryomodules meet LCLS-II spec:
Q0 = 2.8e10, E = 17.1 MV/m,
**$P_d$/CM = 86W**

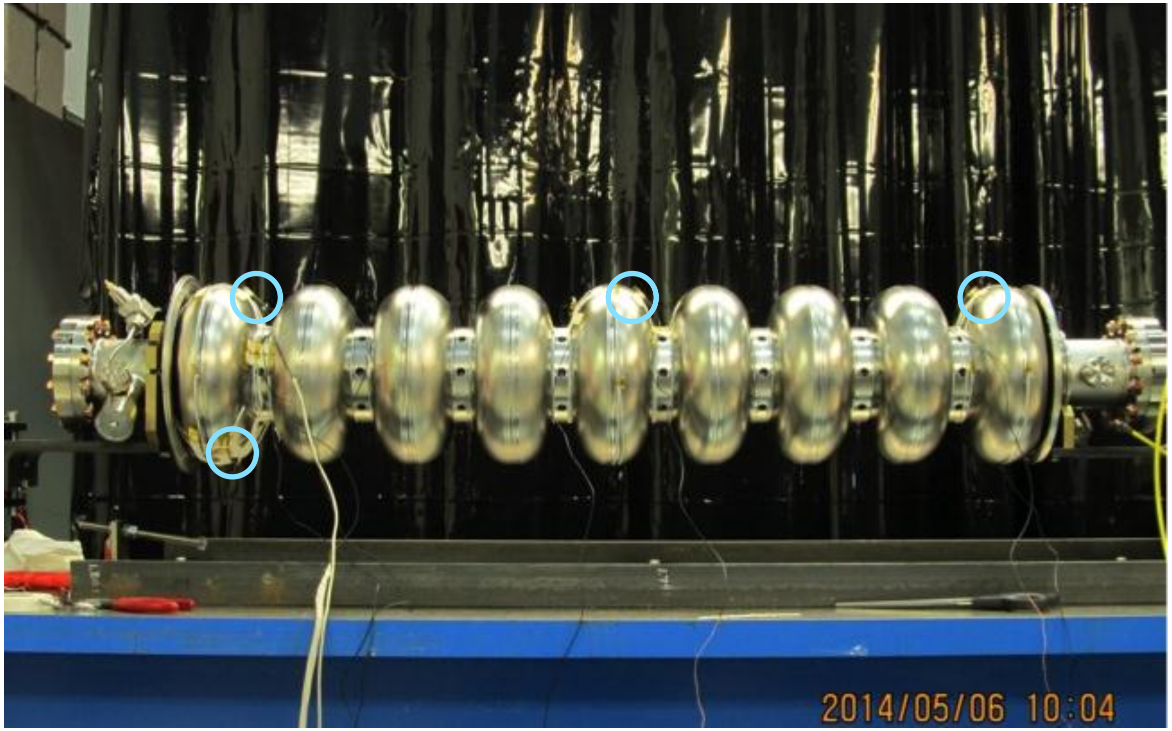
E_acc – Average 19.2 MV/m

***E_acc (CM) ~ 0.9 E_acc_usable (VTA)***
***E_acc (CM) ~ 17.1 MV/m***



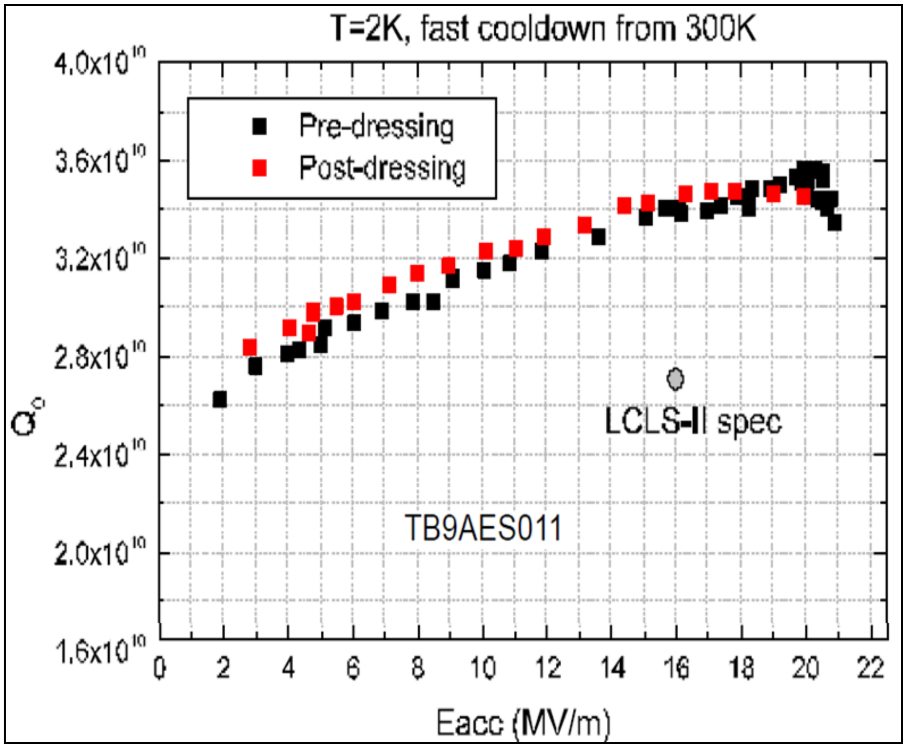
# Ideal cooldown/shielding evaluation on Dressed doped 9-cell cavities

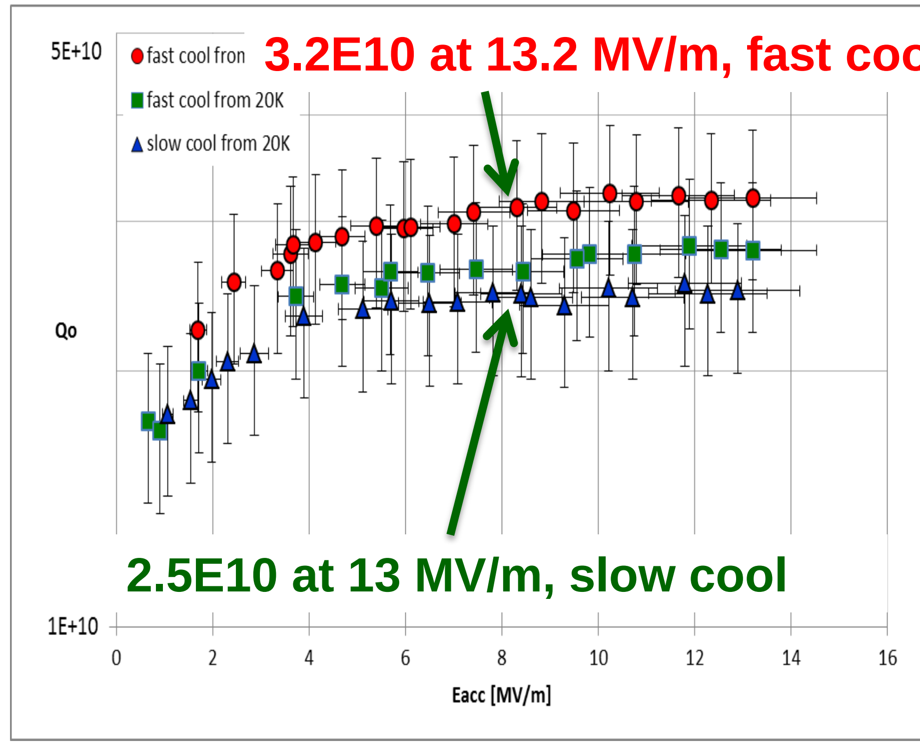
- 2 cavities dressed to ILC HV with 4 flux gate probes and 4 T sensors installed on cells,
- 4 will dressed to LCLS-II helium vessel (2 tested at FNAL, 1-Cornell, 1 JLAB). All tested in VTS first.
- Goal: study how to achieve previously described ideal cooling conditions in horizontal dressed configuration




# Translation from VTS bare cavity to VTS dressed cavity and horizontal cryostat (proof of principle).

**FNAL dressed(ILC type HV) cavities tested in VTS @ Cornell horizontal test cryomodule (B< 3 mGauss). Specific CM environment matter**




Dressing preserve high Q if cooled down properly
Parameters of Cool down to be optimized in DV studies

# FNAL/JLAB cavities for Prototype CM - status

| | 1st pass | 2nd pass | Q @2K, 16MV/m | Quench MV/m | Status |
|---|---|---|---|---|---|
| TB9AES021 | OK | | 3.3e10 / 2.3e10 | 24 | DRESSED – tested HTS |
| TB9AES027 | OK | | 3.6e10 / 2.6e10 | 21 | DRESSED in HTS |
| TB9AES028 | | OK | 4e10 | 25.5 | Lined up for dressing |
| TB9AES020 | | quench | 4.1e10 | 15 | Optical inspection |
| TB9AES024 | OK | | 4.75e10 | 25 | Lined up for CM |
| TB9AES019 | OK | | 3.75 | 20 | Lined up for CM |
| TB9ACC015 | OK | OK | 3.5e10 | 24 | Lined up for CM (needs transition rings) |
| TB9AES026 | OK | | 2.75e10 | 21.5 | Lined up for CM |

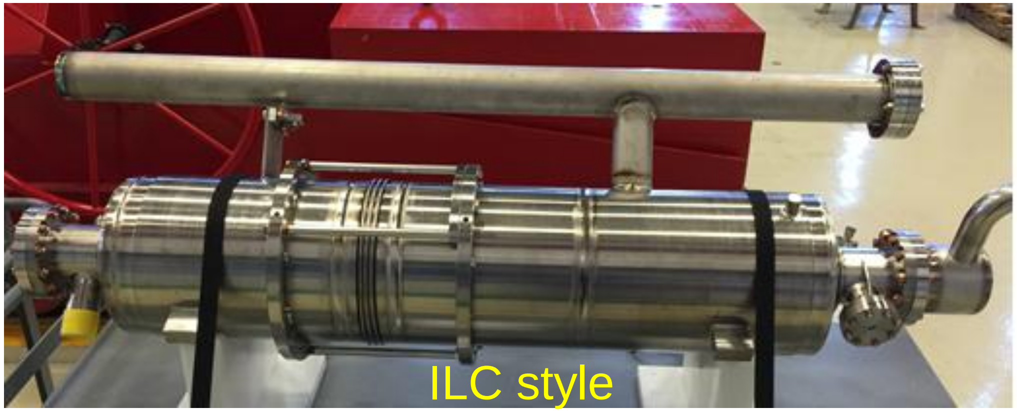
Fermilab

| | | | | | |
|---|---|---|---|---|---|
| **TB9AES031** | | **ok** | **3.1e10** | **19.4** | **In Transition to FNAL** |
| TB9AES032 | | | 2.4e10 | 18.4 | Prepping for test |
| TB9AES033 | | ok | 3.3e10 | 21.6 | Nbti flange test @ JLab |
| TB9AES034 | | | NA | 11.2 | Prepping for qualif test |
| TB9AES035 | | ok | 3.0e10 | 23.6 | @ FNAL DRESSING |
| TB9AES036 | | | 3.8e10 | 17.5 | Prepping for test |

JLAB

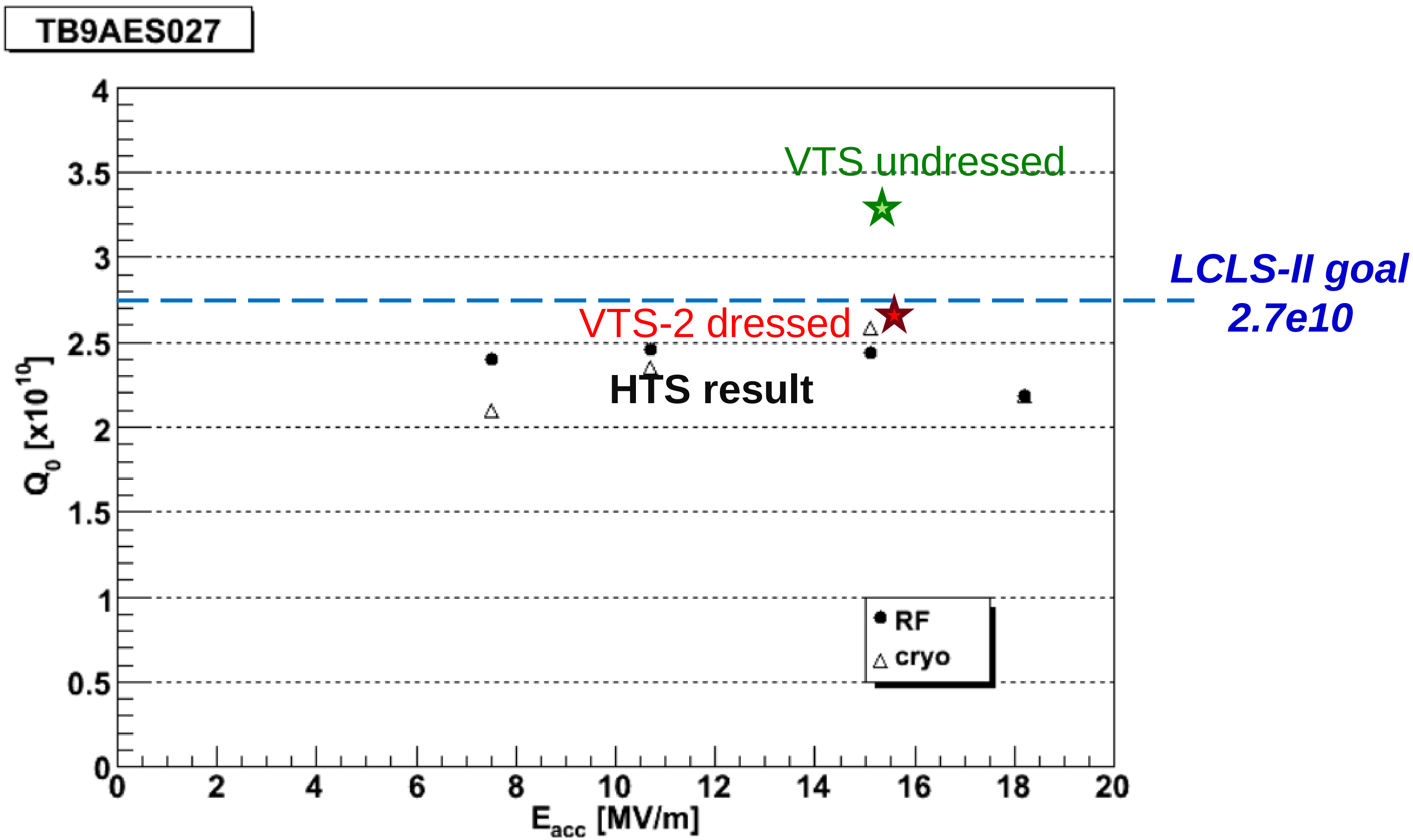
# HTS high Q results *12.2014 – 02.2015*

| Cavity | LHe Tank type | HT Test # | Q0- VT (e10) | Q0- HT (e10) | ΔR res (VT→HT) nΩ |
|---|---|---|---|---|---|
| TB9ACC012 | ILC | HTS-1 (F) | 3.4 | 2.8 | 2 |
| TB9AES011 | ILC | HTC9-1 (C) | 3.5 | 3.2 | 1±2 |
| TB9ACC012 | ILC | HTC9-2(C) | 3.4 | 2.7 | 2±2 |
| TB9AES018 | LCLS-II | HTS-2 (F) | 3.1 (?) | 2.2 | 4 |
| TB9AES018 | LCLS-II | HTC9-3(C) | 3.1 (?) | 2.2 | 4±2 |
| TB9AES021 | LCLS-II | HTS-3 (F) | 3.3 (2.3*) | 2.3 | <1 |
| TB9AES027 | LCLS-II | HTS-4 (F) | 3.3 (2.6*) | 2.5 | <1 |


ILC style


LCLS-2 style

# LCLS-II Dressed cavity in HTS




N.Solyak, FNAL meetiing, March10, 2015

# Design Verification program

# LCLS-II CM design verification program

**Goals:**

- **Validate critical technical decision needed for CM design complete.**
- **Provide test stand for cavity/magnet qualification before installation in CM.**
  - *Prototype CM's complete Dec 2015. All cavities will be tested at VTS, ¼ in HTS*

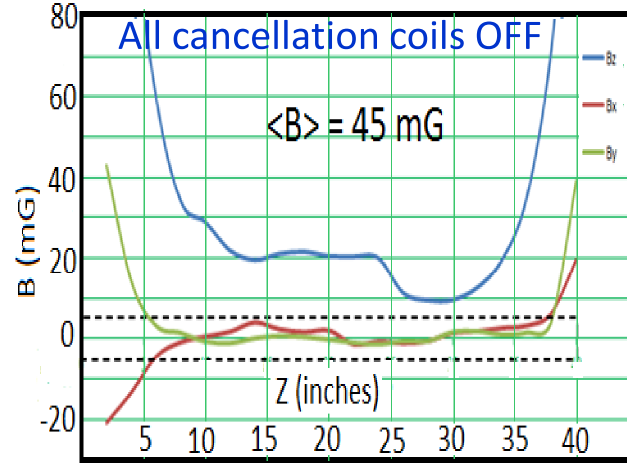
**Critical tests needed to prove technical decisions (HTS):**

- ***Performance of dressed high-Q cavity in cryomodule: Q > 2.7e10 @16 MV/m***
- ***Verify HOM coupler and feedthru designs @ 18 MV/m CW***
- ***Main coupler design: $Q_L$=4.e7; RF cw power = 7 kW with full reflection***
- ***Test LCLSII-type Helium Vessel, magnetic shielding, end-lever Tuner (+piezo)***
- ***Resonance frequency control and microphonics studies (hardware, algorithm)***
- ***Tuner components tests, including reliability studies***

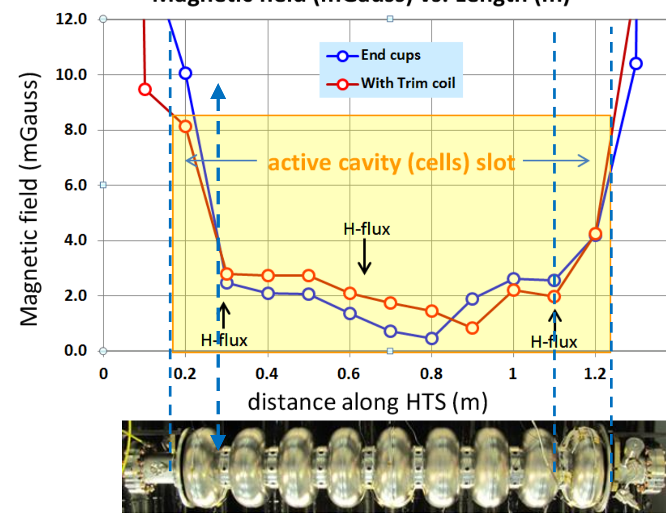
**Testing magnets and Tuner components in cryogenic and other facilities**
**Stand 3, STC, etc..**
**Collaboration with Cornell and JLAB on DV program (cross-checking and parallel efforts)**

# Horizontal Cryostat modification for cw tests


One ILC shield, measurement on cavity centerline (RT)




Magnetic field (mGauss) vs. Length (m)



# HTS tests schedule in FY15

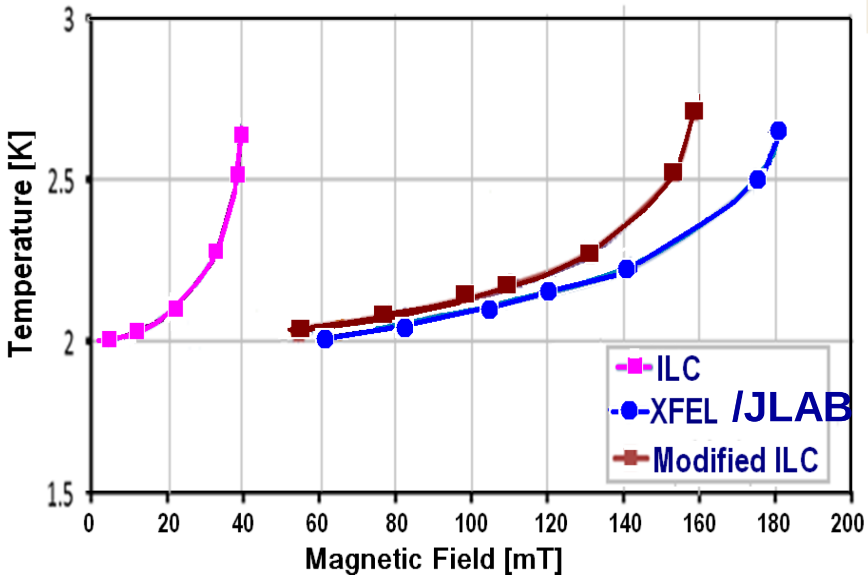
| Dates | Goal | Cavity | Comments |
|---|---|---|---|
| Dec 04-Jan 13 | High Q + Tuner characterization | TB9AES021 (instrumented) | Tuner test SUCCESSFULLY completed |
| Jan 14-Feb 11 | High Q (after He line modifications, plug second fill line and reduce mag fields) | TB9AES021 (instrumented) | HTS and vessel modifications ongoing, microphonics studies/ passive vibration mitigation |
| Feb 12-March 23 | High Q / Tuner test | TB9AES027 (instrumented) | |
| Apr 01 – May-01 | **Fundamental Power Coupler Test #2** | TB9AES021 (instrumented) | Coupler mounted on cavity in clean room. Improved therm.connection / instrum. |
| May 04–Jun 05 | Fully Integrated Test #1 | TB9AES027 (instrumented) | First cavity qualified for string |
| Jun 8 – Jul 03 | Fully Integrated Test #2 | TB9AES021 (instrumented) | Second cavity qualified for string |

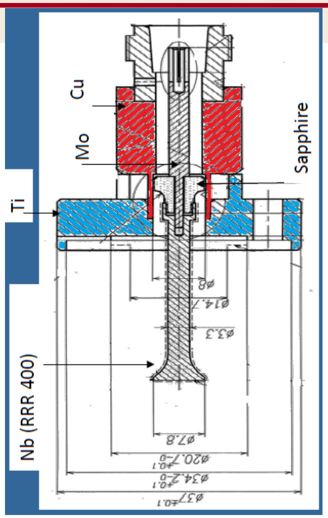
Note: HTS commissioning and tests of HOM and Main coupler completed at 2014

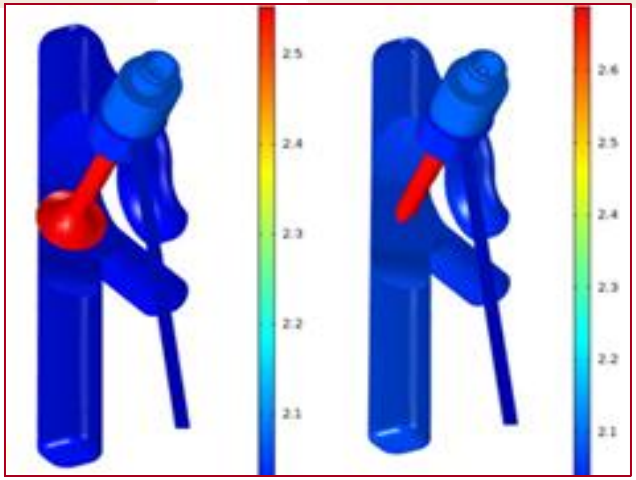
# FNAL HTS schedule- now to PCM – PART II: STRING QUALIFICATION

| Dates | Goal | Cavity | Comments |
|---|---|---|---|
| July 06 – July 31 (est) | HTS QUALIFICATION (fully integrated test) | TB9AES028 | |
| Aug 3 – Aug 21 (est) | HTS QUALIFICATION (fully integrated test) | TB9AES024 | |
| April – July | VTS qualification (dressed with HOMs) | TB9AES026<br>TB9ACC015<br>TB9AES020<br>TB9AES019 | (start as soon as HOMs and vessels available) |
| **STRING ASSEMBLY BEGINS (July)** | | | |
| July 1st – July | HTS QUALIFICATION (fully integrated test) ? | TB9AES019 | |

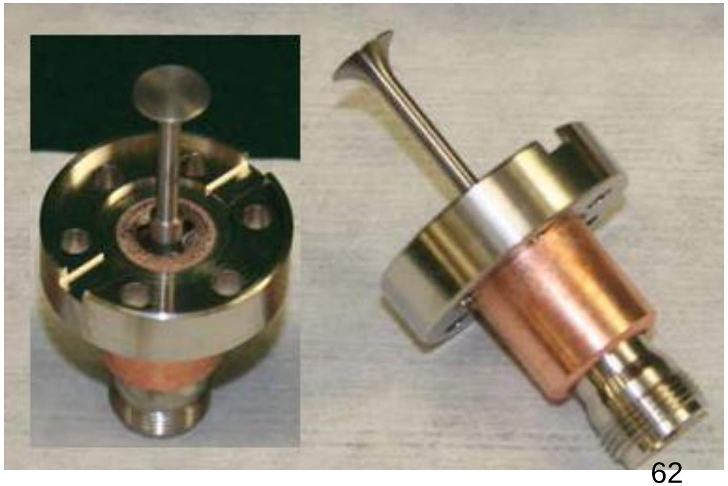
# HOM feed-through for LCLS-II



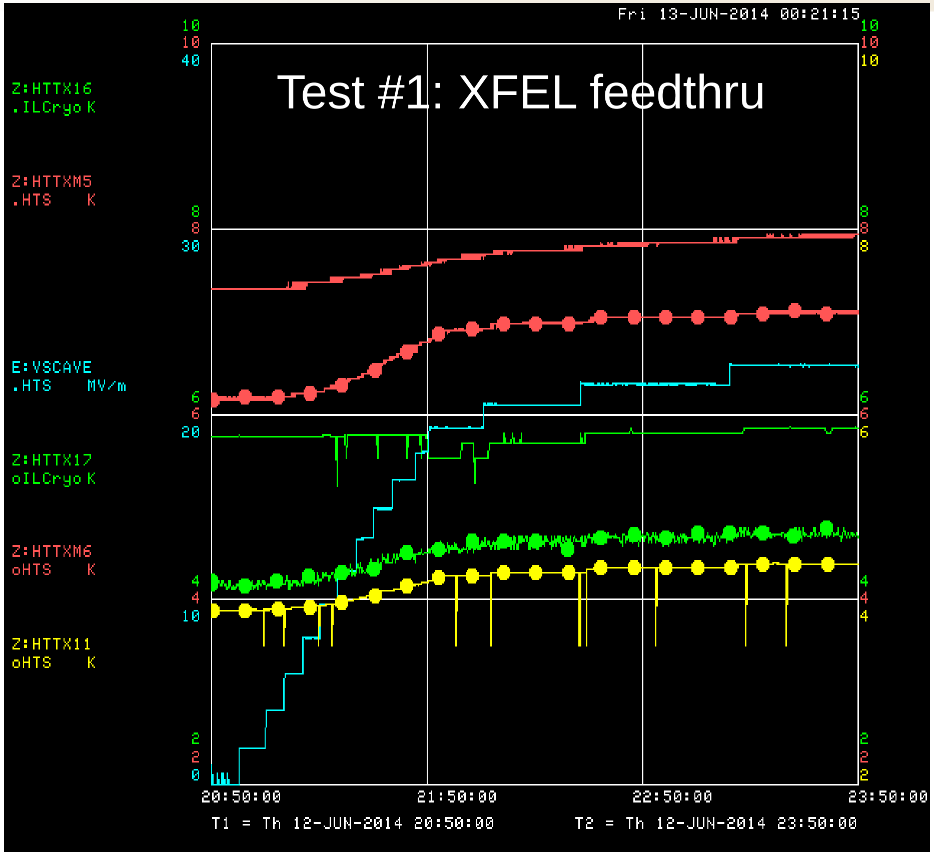



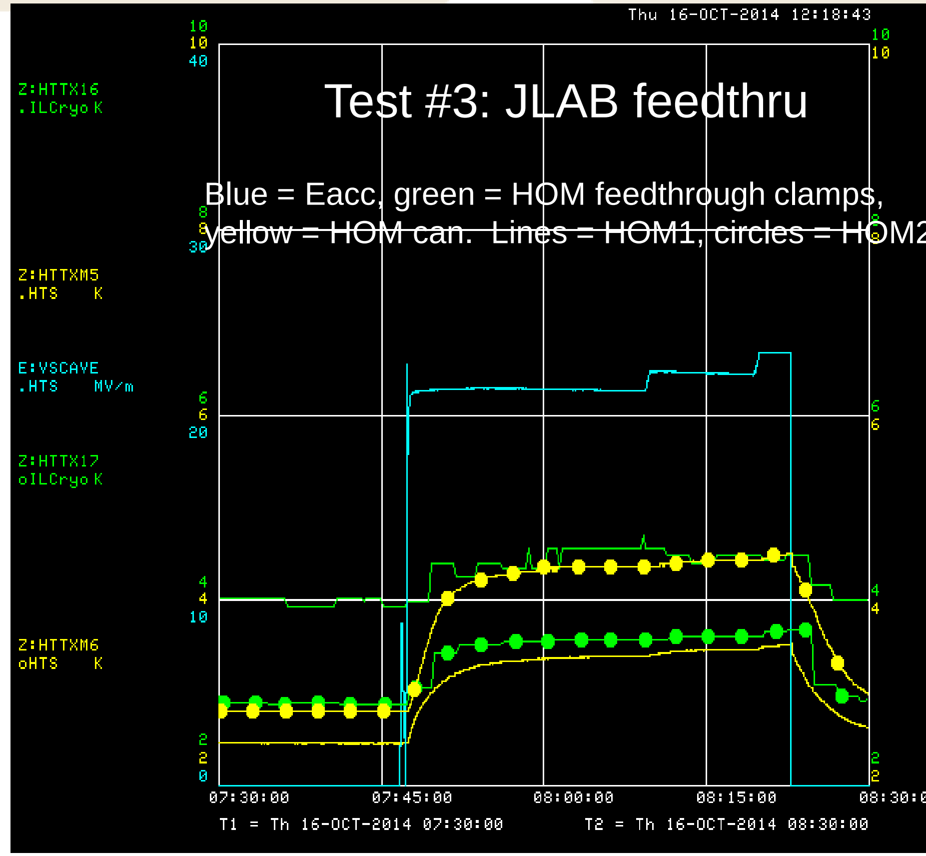
XFEL feedthroughs (connected by 2  braids to the 2-phase tube).



- ILC type feedtru limits cw gradient <10MV/m
- With antenna shape modification it is possible to increase limit, but $Q_{HOM}$ will be ~10 times higher
- XFEL/JLAB /FNAL) will be good ~40 MV/m. Need HTS test to prove at 18 MV/m in cw mode
- Further improvement is possible (pre-product. CM delay; $Q_{ext}$ increase)

# HOM feedthrough heating




- 1.8K, B-field comp'd,8pi/9 mode, 23 MV/m in end cells
- JLAB: ~2.7°rise on HOM body, ~0.85°K on feedthrough
- XFEL/DESY: ~1°K rise on HOM body and ~0.5°K on feedthrough
- HOM power out was ~300 mW (JLAB)

# Power coupler prototype Test in HTS

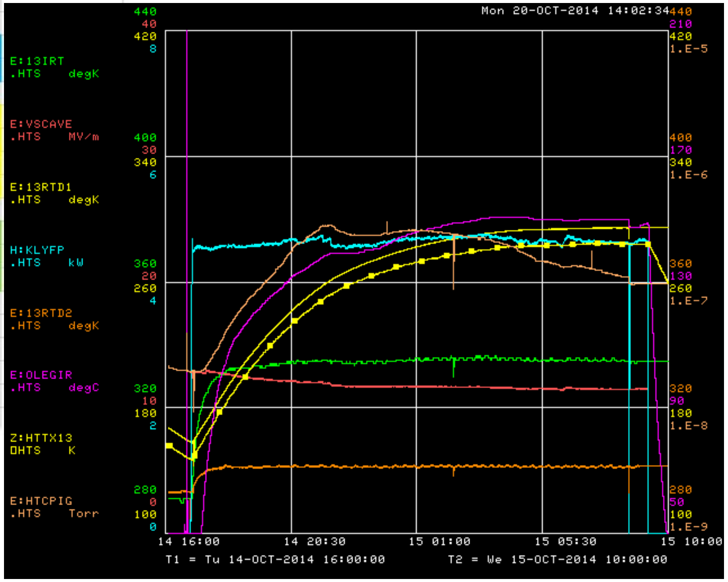
**LCLS-II FPC is based on TTF3 design with 2 major modifications:**

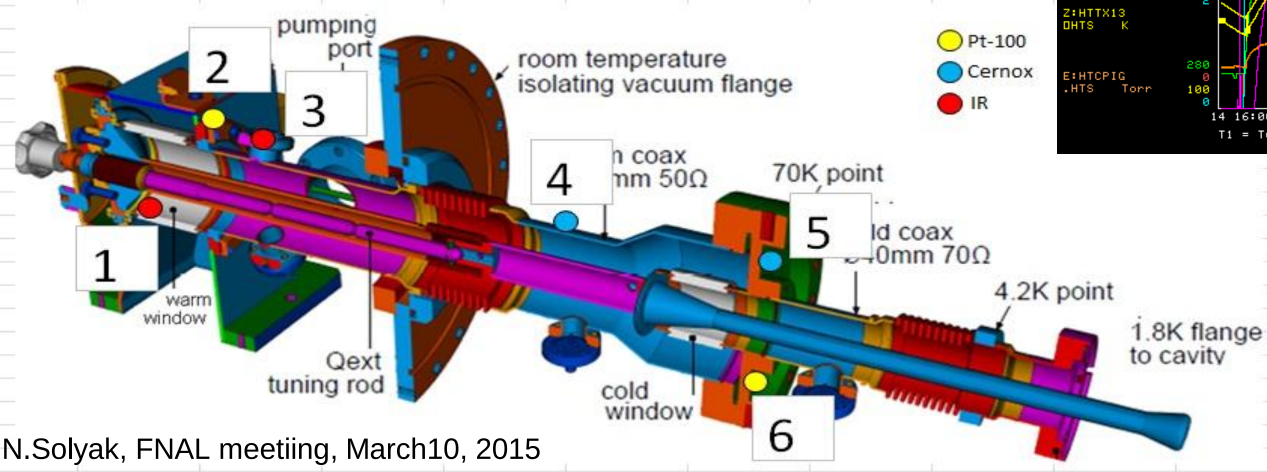
- ***Shorter antenna (-8.5mm) and***
- ***150 µm Cu plating in inner conductor***

7 kW cw power with full reflection

| | | 1 | 2 | 3 | 4 | 5 | 6 | warm vacuum |
|---|---|---|---|---|---|---|---|---|
| | H:KLYFP [kW] | E:13IRT [K] | E:13RTD2 [K] | E:OLEGIR [K] | Z:HTTXM4 [K] | Z:HTTX13 [K] | E:13RTD1 [K] | E:HTCPIG [Torr] |
| baseline | | | | | | | | |
| 09 OCT | 0 | 288 | 291 | <323 | 134 | 110 | 116 | 1.50E-008 |
| off-resonance | | | | | | | | |
| 01 OCT | 1 | 305 | 298 | <323 | 164 | 136 | 143 | 2.00E-008 |
| 11-12 OCT | 3 | 310 | 296 | <323 | 202 | 173 | 181 | 7.30E-008 |
| 12 OCT | 6 | 329 | 300 | 394 | 268 | 249 | 256 | 3.70E-007 |
| on-resonance (QL=1e+07) | | | | | | | | |
| 14-15 OCT | 4.5 | 335 | 301 | 423 | 293 | 284 | 295 | 2.80E-007 |
| 16-17 OCT | 6 | 385* | 333 | 483* | 310 | 315 | 325 | 6.50E-07 |

*=saturation



# Design/prototyping of the CM components

- Cavity helium vessel and magnetic shielding
- Fast/Slow Tuner for "short-short" cavity
- Magnet package (splitable, conductively cooled)

No yet plans for testing

- BPM → adopt XFEL button type BPM
- Beam Line Absorber → adopt XFEL design

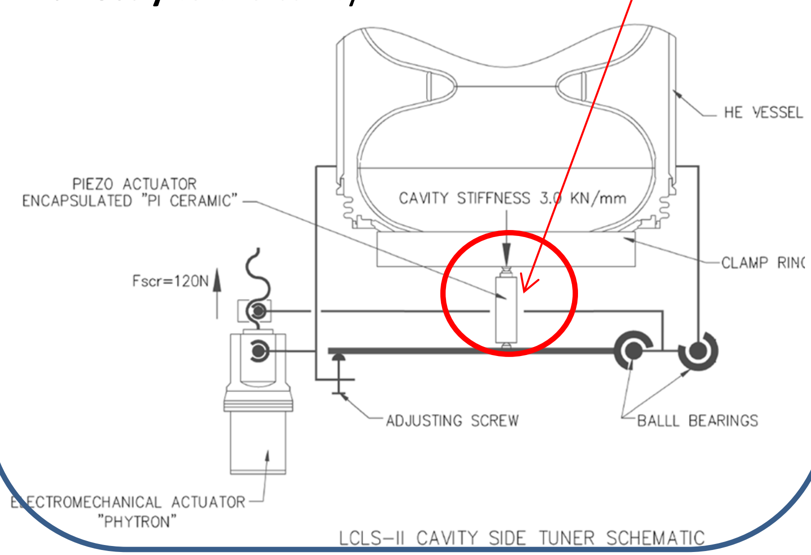
# LCLS II Tuner: specifications

| | LCLS-II | XFEL | SACLAY 1/ Piezo modified tuner/ BESSY tests results |
|---|---|---|---|
| *Parameters* | *Value* | *Value* | *Value* |
| Cavity Frequency | 1.3GHz | 1.3GHz | 1.3GHz |
| Cavity bandwidth | 30Hz | 200Hz | |
| Cavity elongation tuning | 340Hz/um | 340Hz/um | 340Hz/um |
| Cavity Spring Constant | 3N/um | 3N/um | 3N/um |
| **Slow Tuner freq. range (expected)** | **250kHz** | **200kHz** | **200kHz** |
| **Slow Tuner freq. range (max)** | ***420kHz*** | ***600kHz*** | ***750kHz*** |
| Slow Tuner cavity displament(exp./max) | 740/1300um | 1900um | 1900um |
| Slow/Coarse tuning sensitivity | 1-2 Hz/step | 1Hz/step | 1Hz/step |
| **Fast Tuner cavity freq. range** | **1KHz** | **1KHz** | ***700Hz*** |
| Fast Tuner dimentional range | 3um | 3um | *2um* |
| **Fast Tuner tuning resolution** | **1Hz** | **10-20Hz** | ***~0.2Hz*** |
| Fast Tuner stroke resolution | 3nm | 30-60nm | *0.6nm* |
| Fast Tuner response bandwidth | 5kHz | 1kHz | *900Hz* |
| **Min. tuner stiffness** | **30N/um** | **20N/um** | **20N/um** |
| Min. tuner mechanical resonance | 5kHz | 5kHz | 5kHz |
| Tuner operating condition | insulated vacuum T=20-60K | insulated vacuum T=20-60K | insulated vacuum T=20-60K |
| Slow Tuner / electromechanical lifetime (20years) | 1000 spindle rotation | 1000 spindle rotation | 1000 spindle rotation |
| Fast/piezo Tuner lifetime range | $5^*10^9$ pulses | $5^*10^9$ pulses | $5^*10^9$ pulses |

Fermilab design for "short-short" cavity

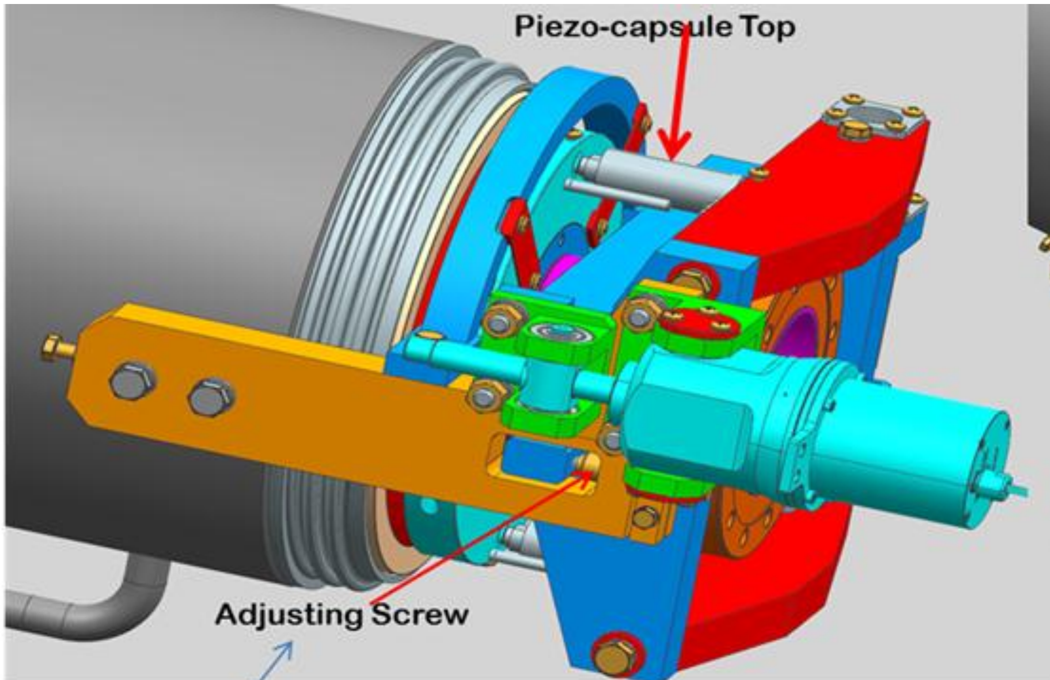
## Tuner Schematics

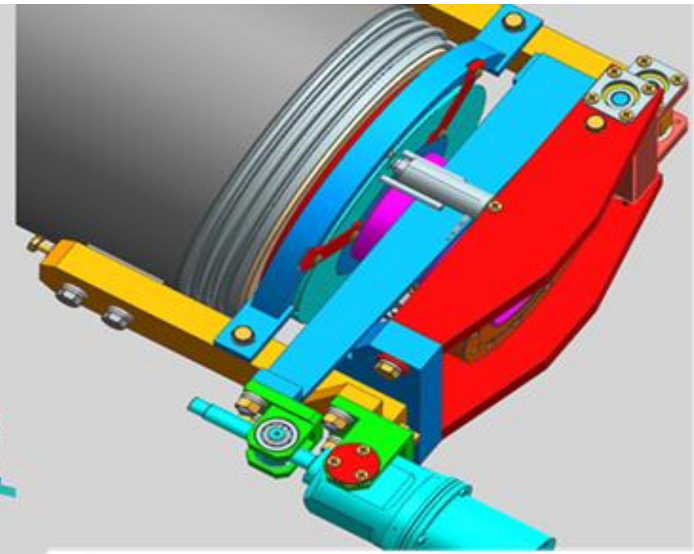
- Slow/Coarse Tuner is double lever tuner (close to Saclay design
- Coarse Tuner ratio 1/20 (Saclay ~1/17)
- Fast Tuner – two piezo installed close to flange of the cavity/translation of **the stroke from piezo directly** to the cavity

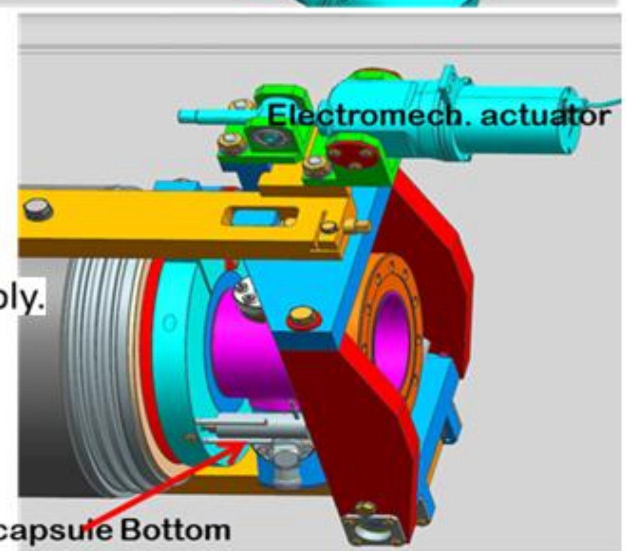



***Cavity has narrow bandwidth (~30Hz) → tight requirements for slow & fast/fine tuning resolution***

# LCLS-II Tuner Design (FNAL)

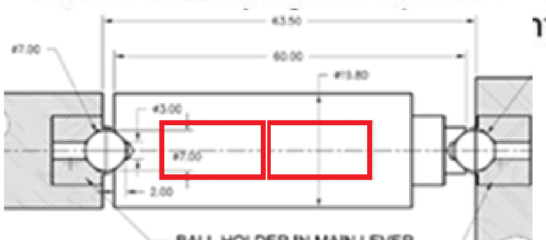


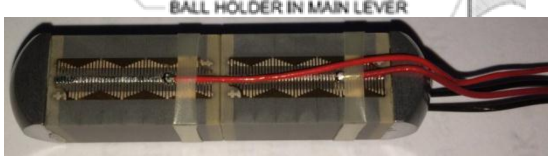






Adjusting Screw to unload

Tuning mechanism to uniformly preload piezo-capsule during initial assembly.

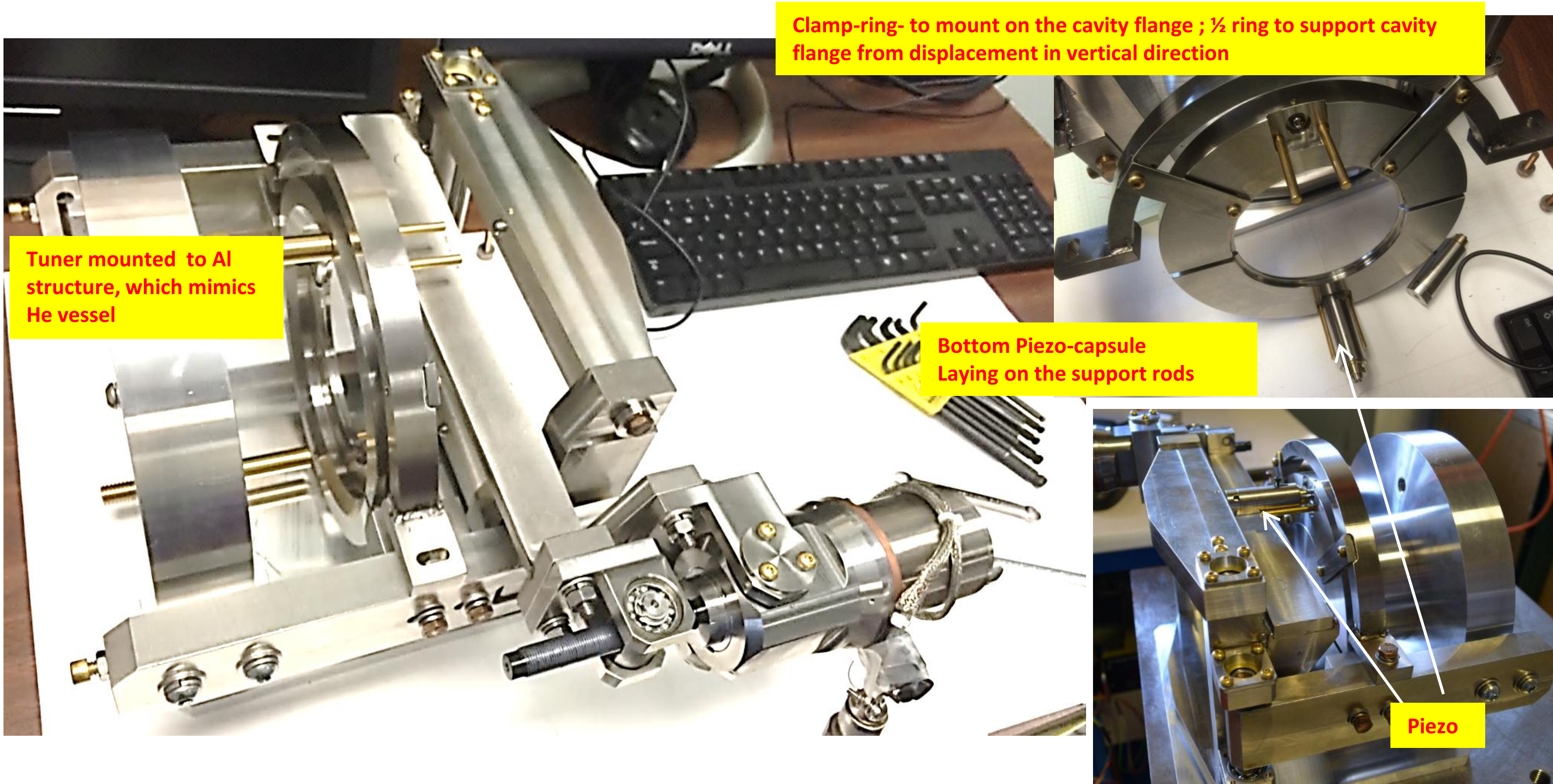


**Capsulated and preloaded piezo (two 18mm glued) from PI ceramics**

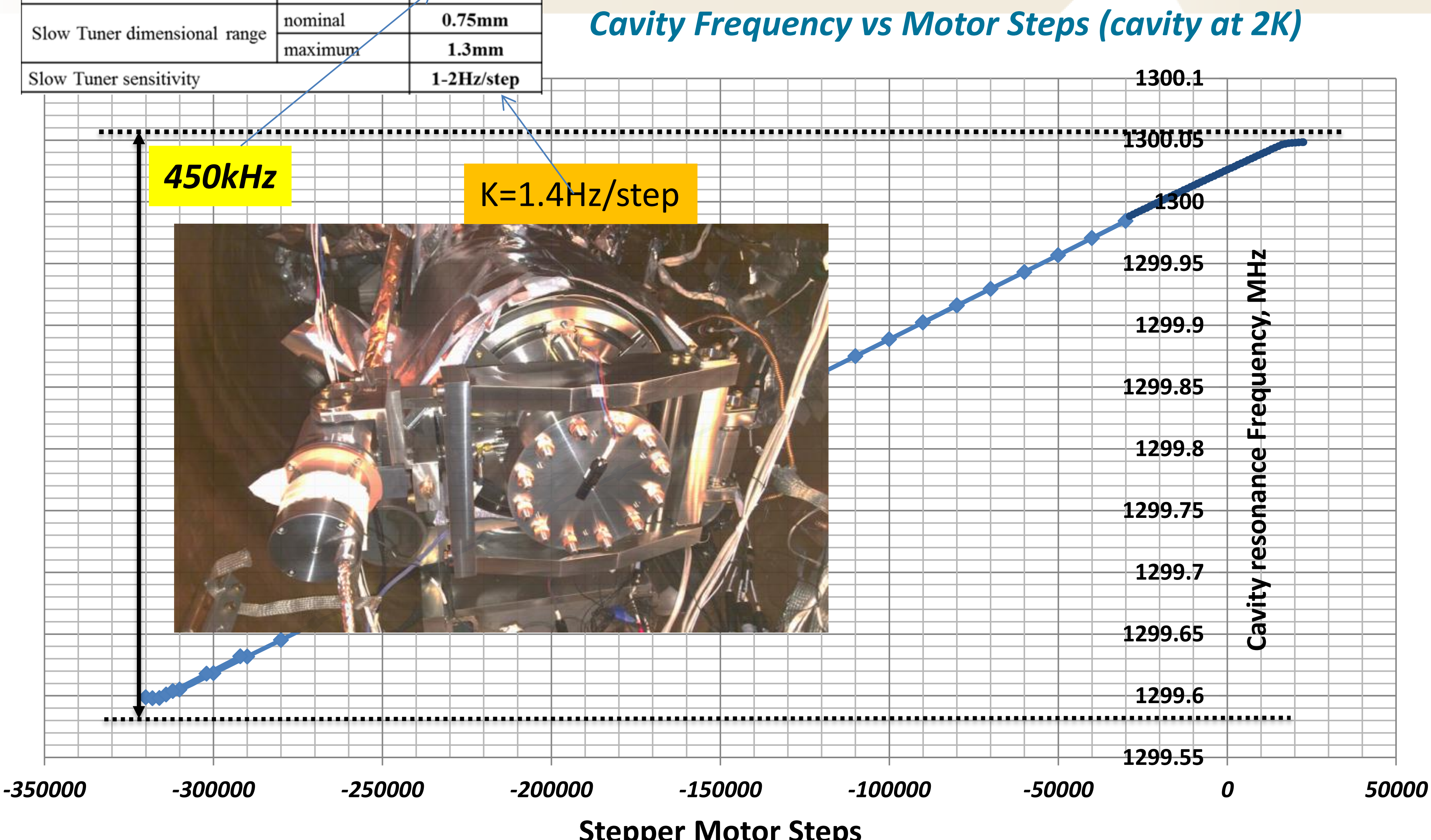
# FNAL Tuner prototype assembly (design details)

- LCLS-II baseline tuner – XFEL (Saclay-I)
- FNAL developed Tuner for “short-short” cavity, available fro pre-production CM
  - Active tuner components replaceable from special port (reliability)



# Slow/Coarse Tuner Performance Test at HTS

| | | |
|---|---|---|
| Slow Tuner frequency range | nominal | 250kHz |
| | maximum | 450kHz |
| Slow Tuner dimensional range | nominal | 0.75mm |
| | maximum | 1.3mm |
| Slow Tuner sensitivity | | 1-2Hz/step |



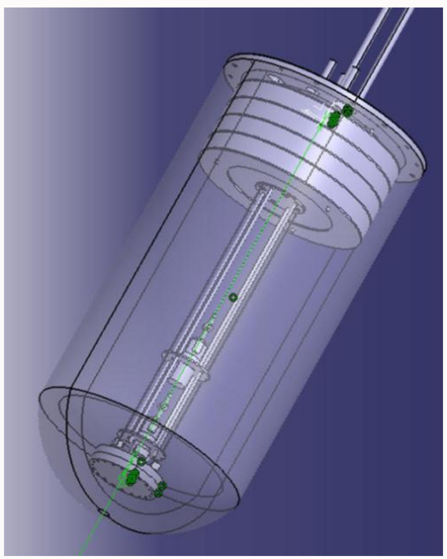
# R&D program on Tuner components

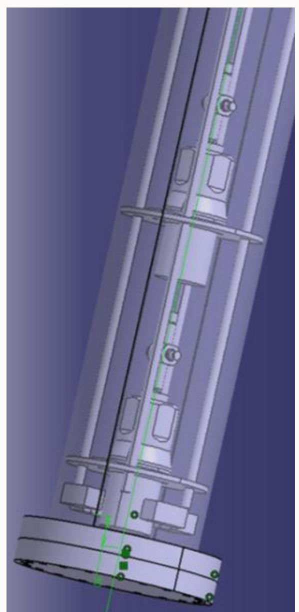
***Study longevity of Tuner's components (actuators and piezo). Two new cold/insulated vacuum test stands under construction at TD:***

- *Test electromechanical actuators (at LN2)*
- *Test Piezo (at LHe).*

**Electromech. actuator lifetime Test Stand.**

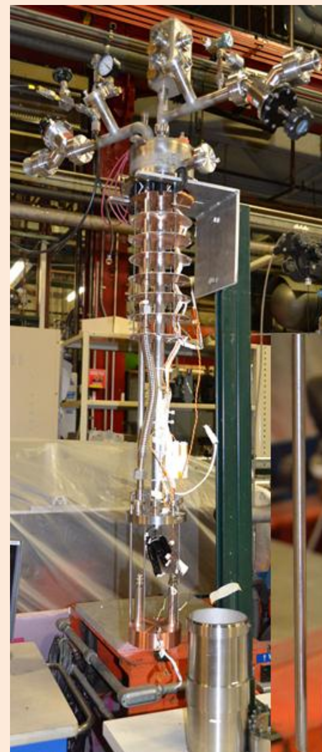
*Goals: study failure mode vs spindle rotations at different working loads*





Piezo Tuner Reliability Test Stand Study Longevity (LN2) vs:

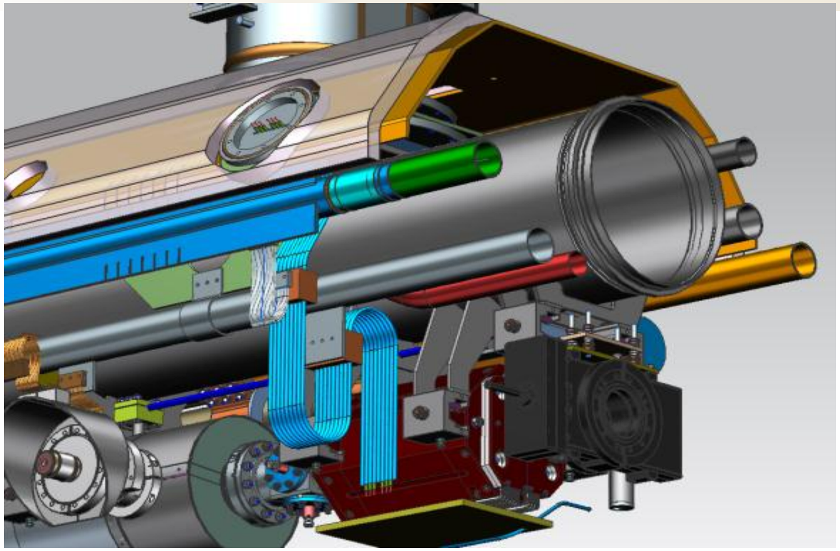
- ***piezo driving voltage***
- ***shape of the pulses (slew-rate)***
- ***number of pulses***
- ***overheating of the piezo***
- ***radiation damage***
- ***etc …***

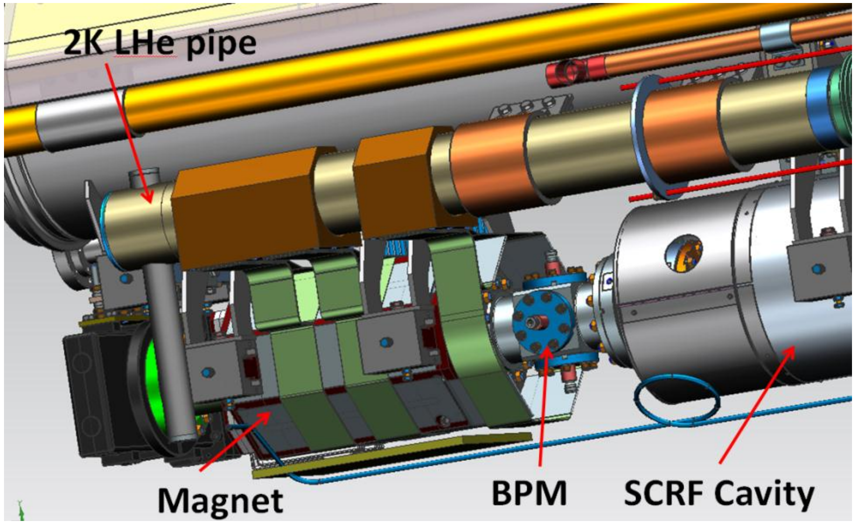



***Inserts into LHe dewar with cryo/vacuum & electrical connections***

# Superconducting Magnets

# Conductively Cooled Quadrupole/Dipole magnet



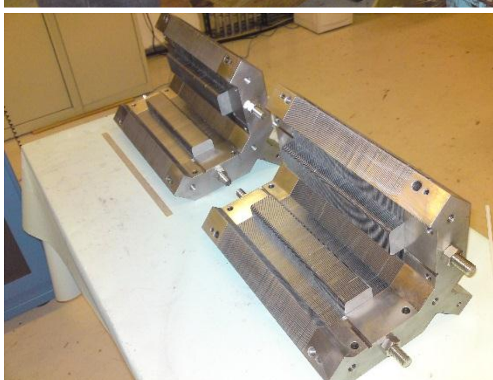


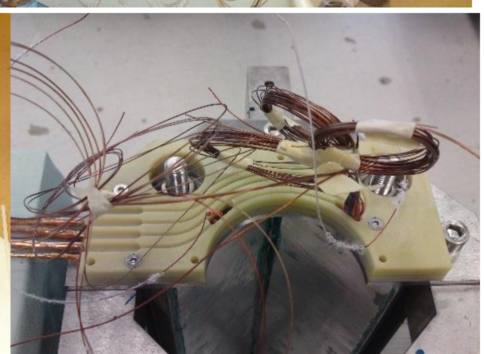

| | |
|---|---|
| Integrated peak gradient ( 10 GeV), T | 2.0 |
| Integrated minimal gradient ( 100 MeV), T | 0.05 |
| Aperture, mm | 78 |
| Dipole trim coils integrated strength, T-m | 0.005 |
| Residual integrated field (magnet unpowered), G-m | 8.0 |
| Residual field on the shielded SCRF (unpowered), mG | < 5.0 |
| Magnetic center offset in CM after installation, mm | < 0.5 |
| Liquid Helium temperature, K | 2.2 |

- **Magnet should be installed at the end of CM, be splittable, and conductively cooled.**
- **LCLS-II design is ased on ILC design built for KEK and ASTA**

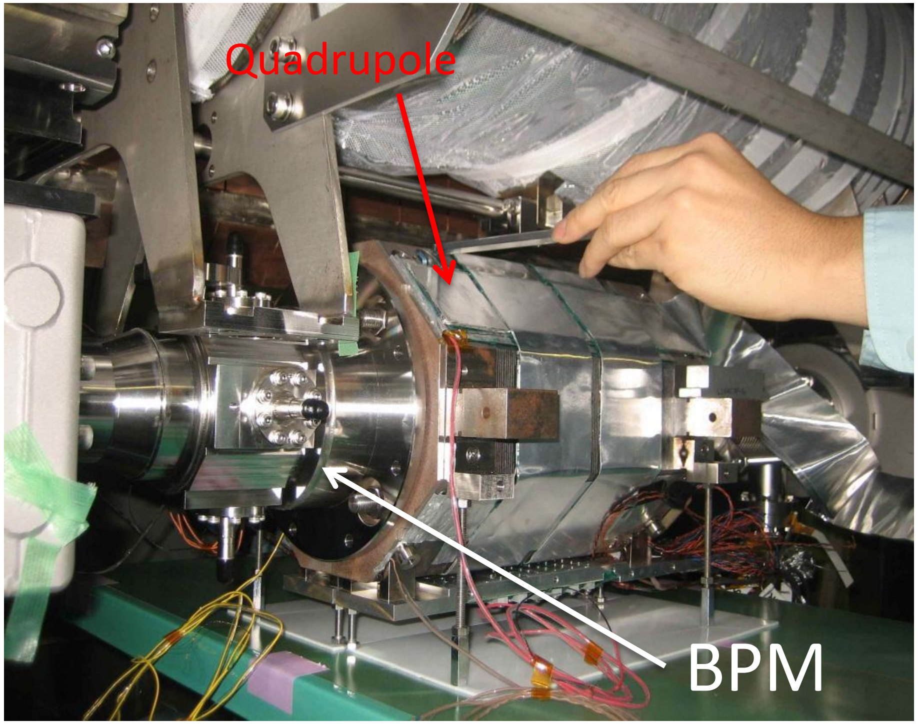
***Vladimir Kashikhin***

# Magnet Package Fabrication





# Quadrupole Assembly and Test at KEK/STF




*A.Yamamoto*

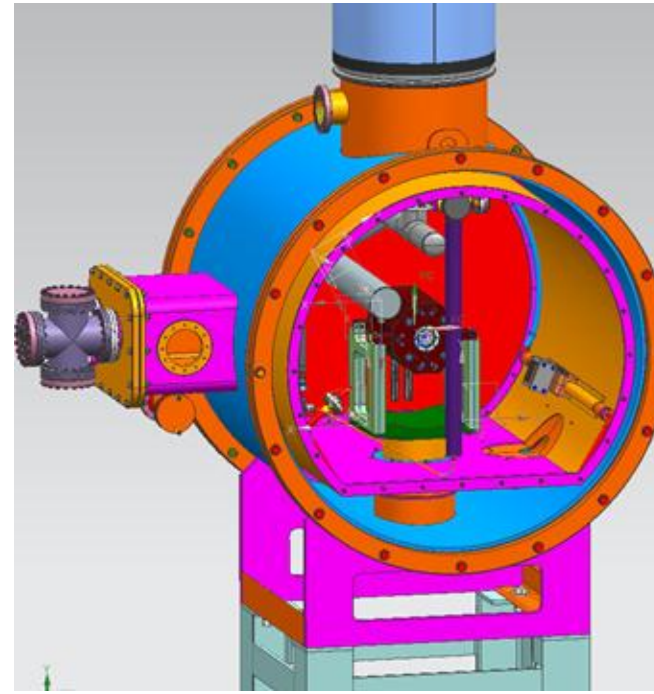
Lifting up the magnet (left) and final assembly (right).

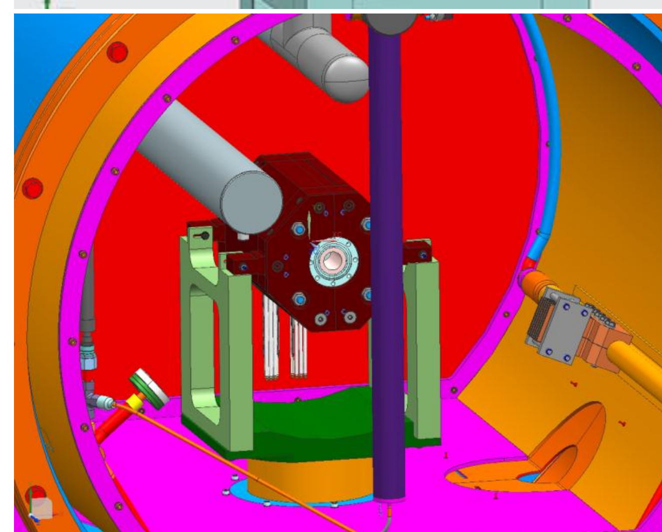
**KEK/STF CM with the magnet prepared for test**
**(with participation of FNAL team )**.

## Current leads and Conduction Cooling Test at STC cryostat

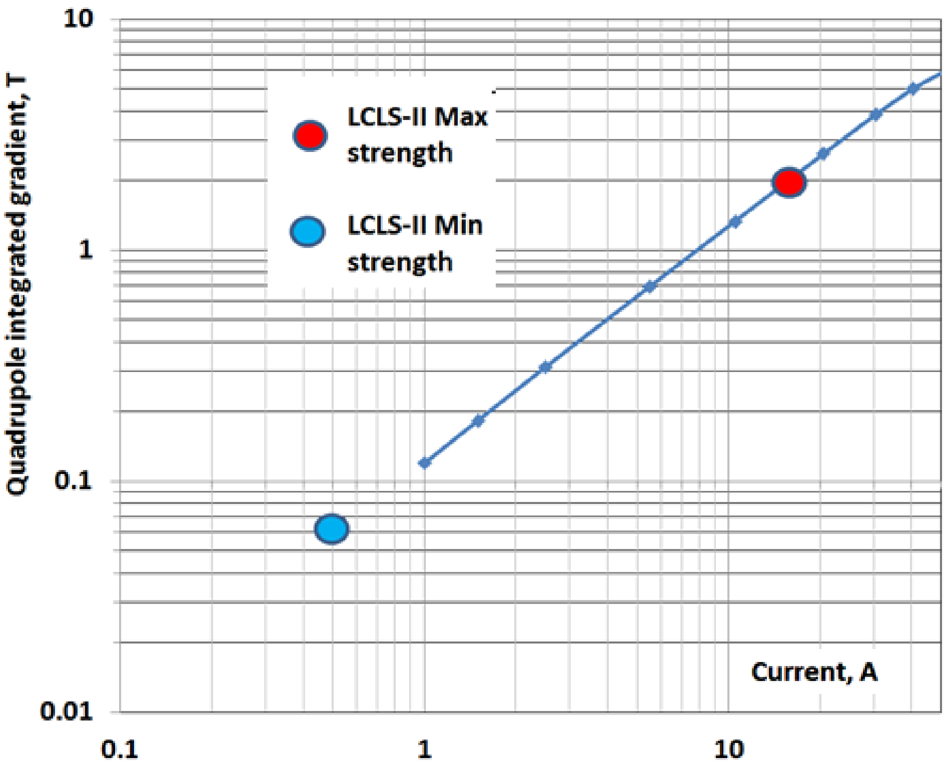
# Magnet Prototype Test at Stand 3

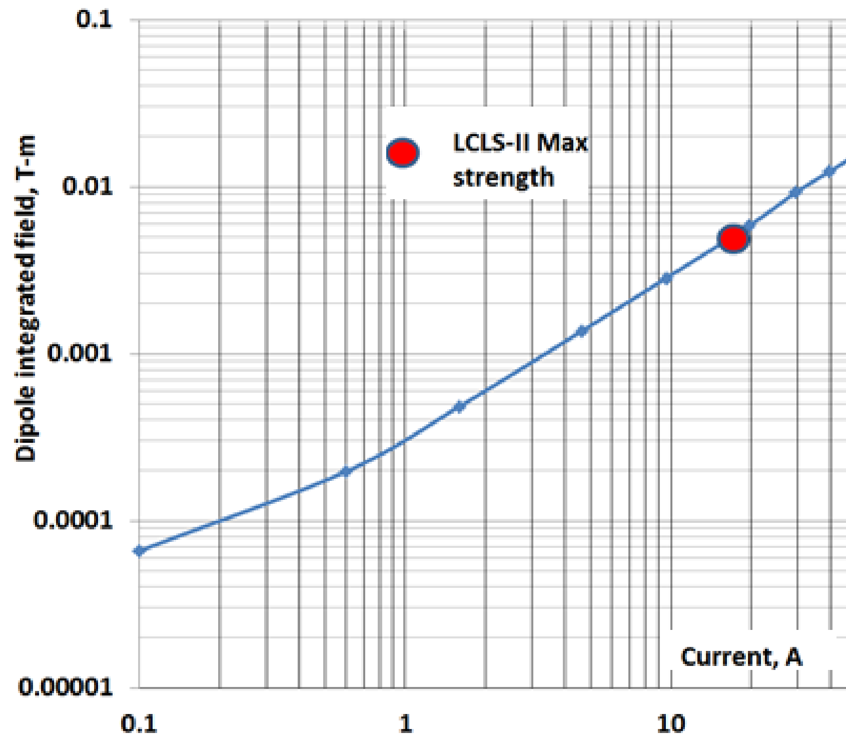

**Magnet cooled down to 4.5 K and tested in the bath cooling mode at Stand 3.**





# Quadrupole Magnet Strength

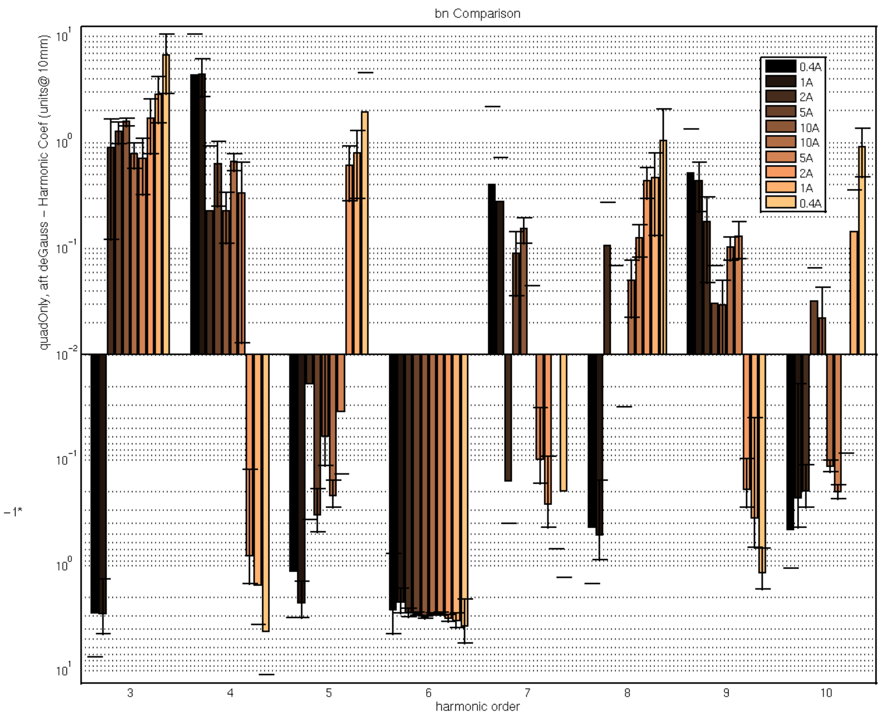


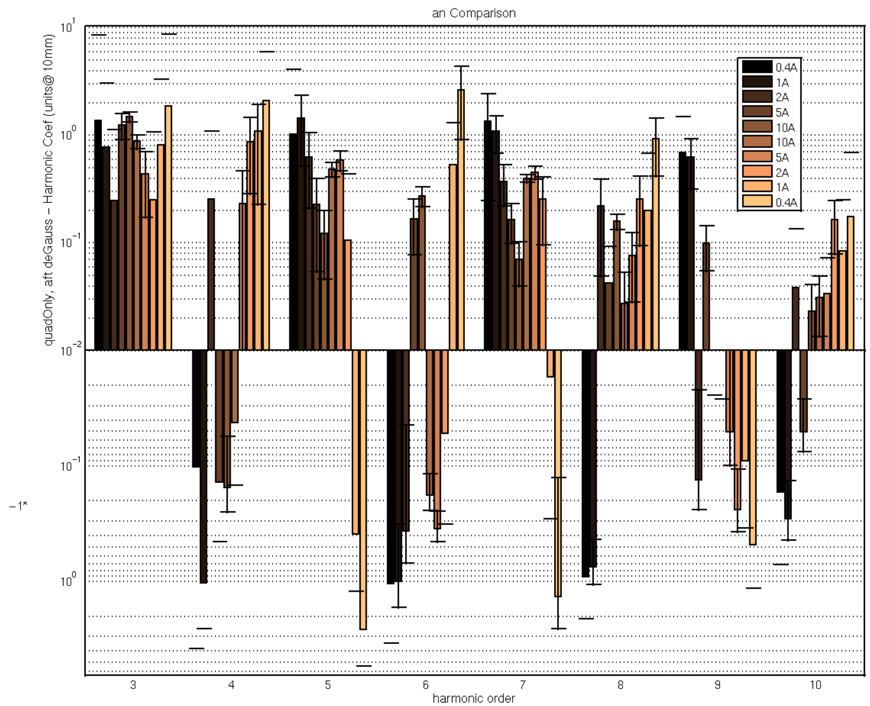




- **Only one quench at 48.5 A during quadrupole magnet ramping up to 50 A during bath cooling test.**
- **2.0 T LCLS-II integrated gradient at 15 A.**

- **No quenches up to 50 A during bath cooling test.**
- **Dipole 0.005 T-m integrated field was reached at 17 A.**

# Quadrupole Geometric Harmonics



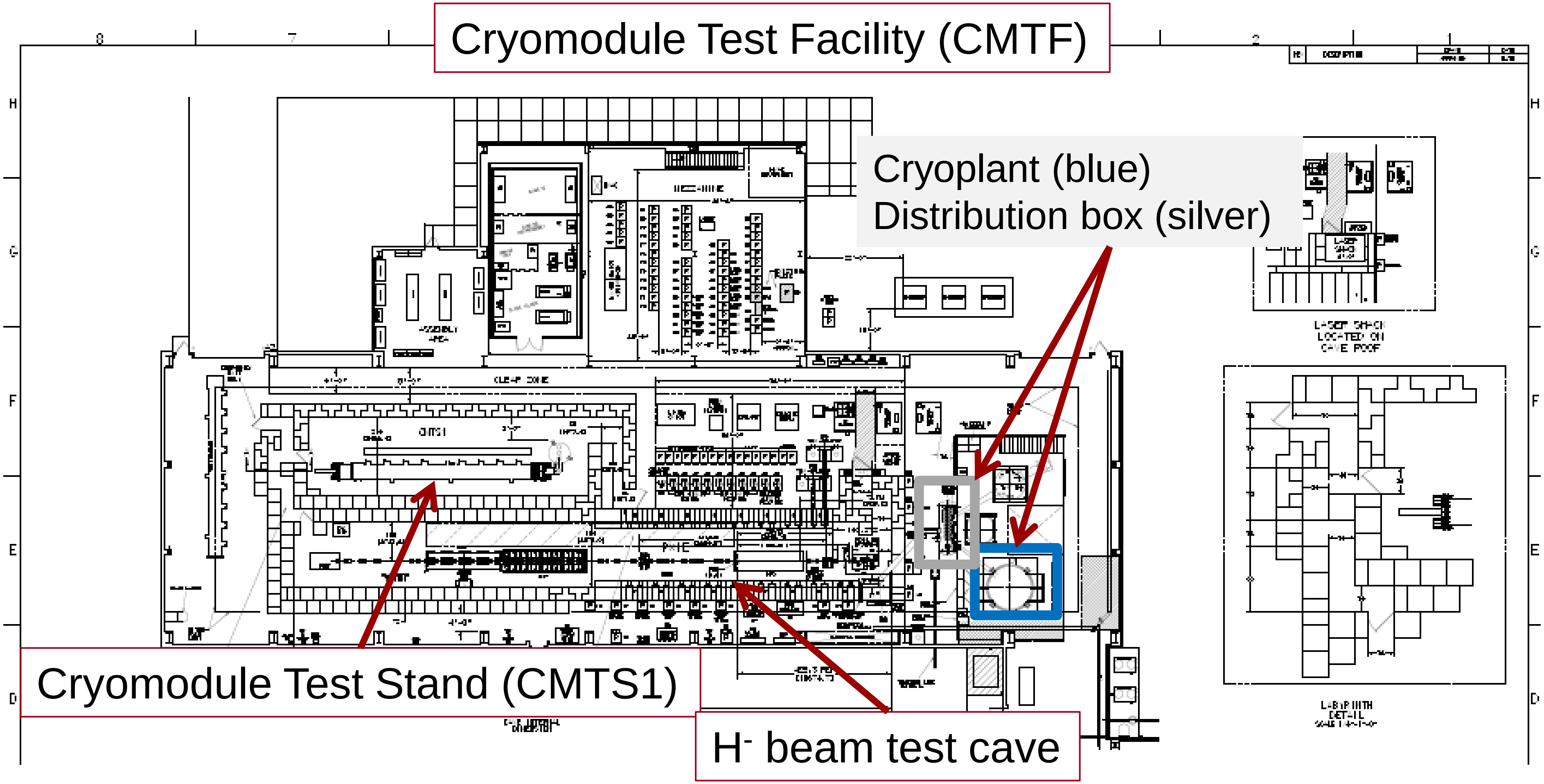




- **To obtain the geometric harmonics they were averaged after measurements with ramping current up from -10 A to +10 A.**
- **In this case excluded: external fields, iron and superconductor hysteresis.**
- **All harmonics are less than 10 units at 10 mm radius.**
- **Additional tests required to demonstrate performance at low field, degaussing and current leads performance**

# LCLS-II FNAL Cryomodule test plan

- *Prototype 1.3 GHz CM test will be rigorous: a complete checkout*
  - *Performance limitations of individual cavities & complete module*
  - *Duration 4 months*
  - *Prototype cryomodule will have more diagnostic instrumentation*
- **New test stand CMTS1**
  - *Commissioning will be necessary, to be completed in advance as much as possible*
- *Production 1.3 GHz – will begin rigorous and assess as program proceeds*
  - Time constraint: Available test period start-to-finish 6 weeks
  - Nominally 3-week test period
- Critical that CM test program is equivalent JLab<->FNAL
- Both 3.9 GHz cryomodules will be tested, after 1.3 GHz

# FNAL cryomodule test stand (CMTS1) layout




Will be ready in advance of the Prototype cryomodule test starting January 2016

# FNAL cryomodule test stand (CMTS1) overview

Multi-use CM Test Stand (LCLS II and eventually PIP II)

Cryoplant (new) is fully commissioned

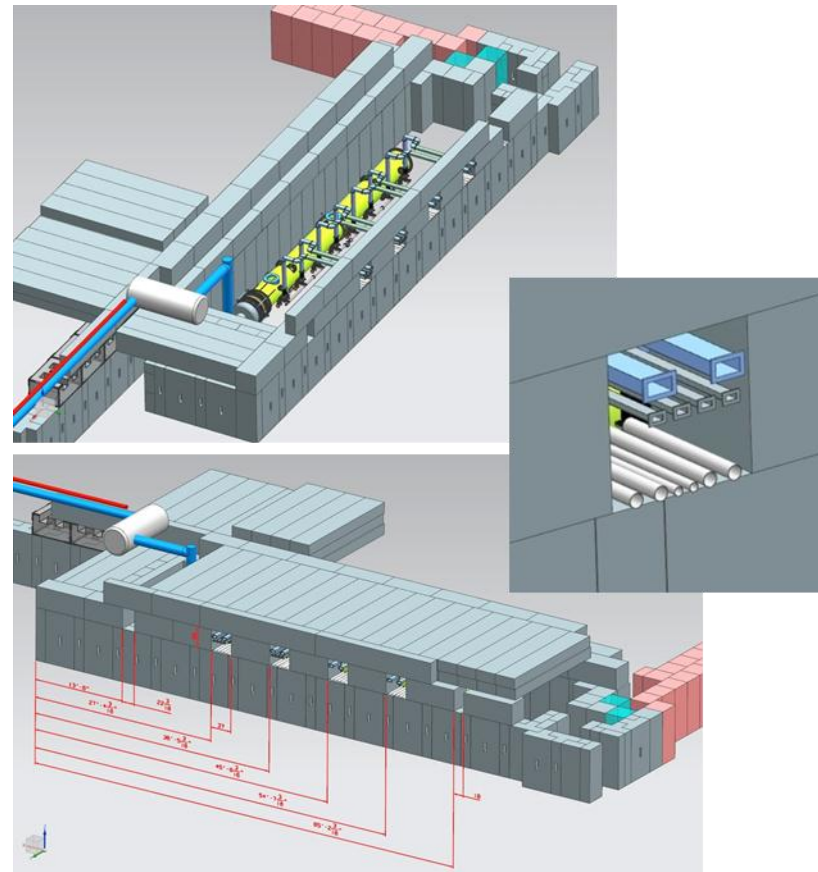
- 500 W at 2K

Design is in progress

- Builds off the NML and DESY experiences
- Floor layout established
- Cryogenic distribution transfer is in procurement
- LLRF based on NML and HTS (CW) systems
- RF power sources supplied by SLAC
- Feed Cap and End Cap supplied by BARC
  - Design complete
  - Production Readiness Review September 2014
  - Fabrication underway, delivery in June 2015

Funding is in place (75% FNAL, 25% LCLS II)

- OHEP is very supportive of this work



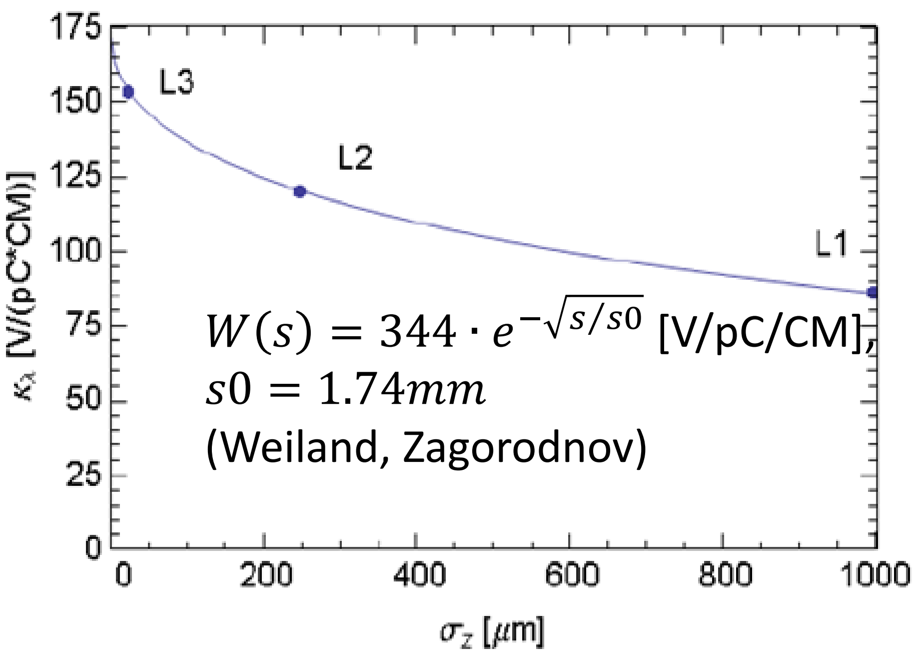
**CMTS1 to be fully commissioned & ready for operation in October 2015**

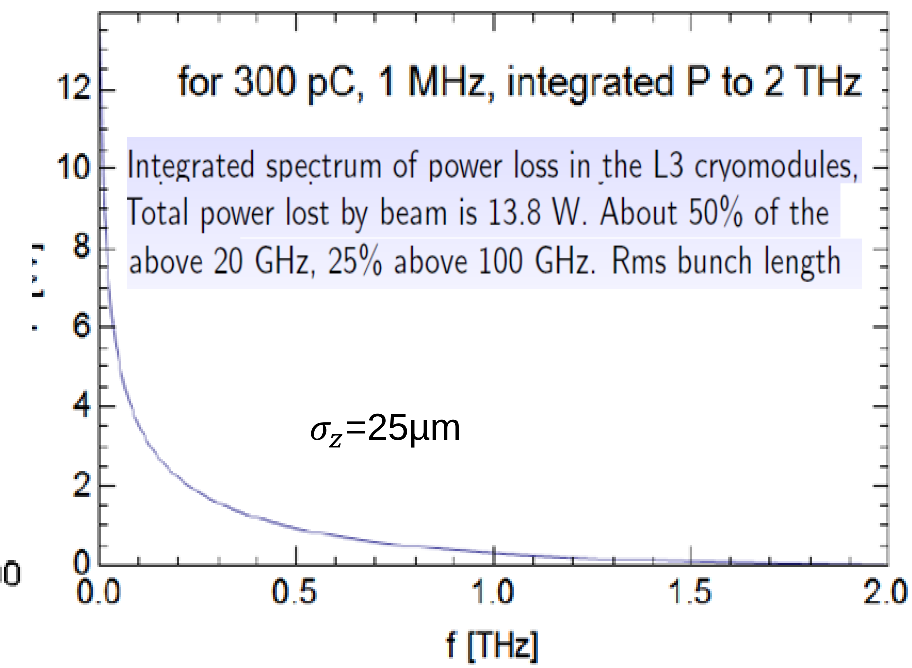
# CMTS1 status photos Feb. 2015


**CMTS1 to be fully operational in Oct. 2015**

# HOMs and Wakes in LCLS-II SC Linac: Steady-state losses

- In LCLS-II, HOM's generated by the beam will add to the power load, especially in the last linac (L3), where the peak current is highest.
- Ceramic absorber (between CMs , tied to 70K) → to absorb the HOM power.
- The HOM power generated by the beam is $P \sim Q^2 \cdot f_{rep}$. The nominal charge Q = 100 pC; however, the combination Q = 300 pC, $f_{rep}$ = 1 MHz, will generate the highest HOM power
- The beam (Q = 300 pC, $f_{rep}$ = 1 MHz) loses **7.7, 10.7, 13.8 W/CM in L1, L2, L3** (except for first two CM)



# Transient Wakes

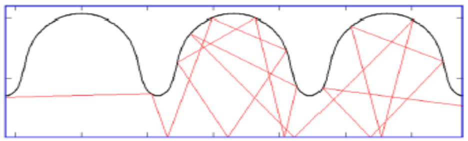
- For a short bunch passing through a periodic structure, it takes on the order of the catch-up distance, $z_{cu}$=$a^2/2\sigma_z$, to reach the steady-state wake. For L3 taking *a = 3.5 cm* & $\sigma_z$= 25 µm, **$z_{cu}$ = 25m**
- When the beam enters the first CM of L3, the first cells loss factor is higher (see LCLS-II TN-13-04). In the first four CMs of L3 losses are: **29.5, 14.5, 13.8, 13.8 W**
- Direct calculation of the transient wake is difficult to do because of the huge number of mesh points involved. However, G. Stupakov /SLAC has obtained the transient wake with Echo using scaling law.

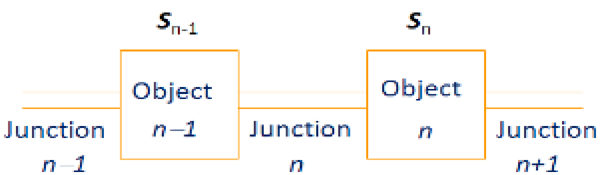
# Wakefield power losses in CM models

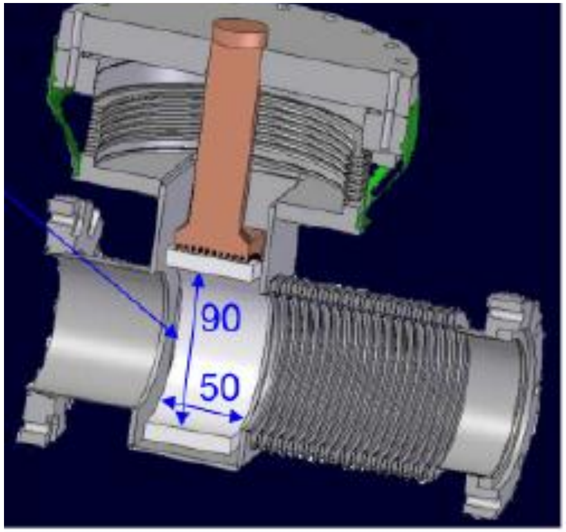
- *Ray Tracing (difussion) model - M. Dohlus*
- *Scattering matrix approach - K. Bane/ G.Stupakov*
- *Simple Analytical Estimation using diffusion approach.(V.Yakovlev / A.Saini)*

$$I_i^{abs} \sim n_i S_i \int P_0(\omega)\,\mathrm{Re}(Z_i\,(\omega)d\omega$$

coarse models: photon tracking

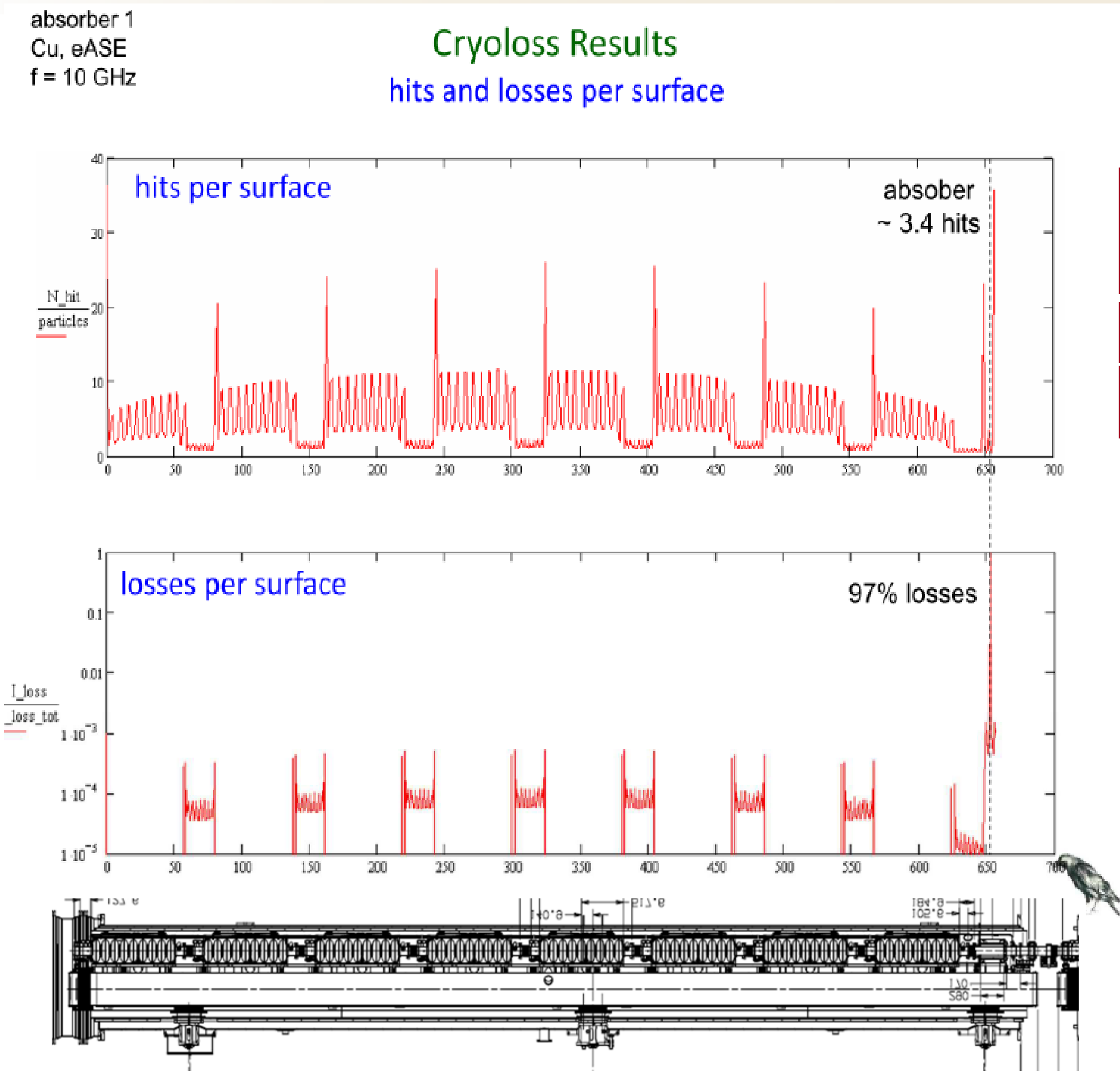





material probe 4: $\mathrm{Re}(\varepsilon) \approx 40\ \varepsilon_0$
$\tan(\delta) \approx 0.70$

# Distribution of power losses in CM (diffusion model)




Distribution of power losses in CM

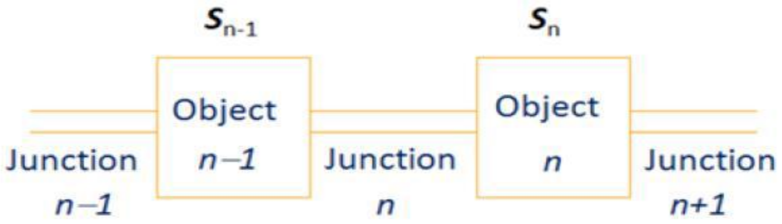
| | $P_{cav}$ (W) | $P_{bellow}$ (W) | $P_{absorb}$ (W) |
|---|---|---|---|
| Cu bellow | 0.07 | 0.76 | 13.0 |
| SS bellow | 0.03 | 7.6 | 6.2 |

- Power dissipation at 2K ( inside the cavity) is negligible.
- Most of HOM power is deposited to absorber in case of copper bellow.
- HOM power is almost equally distributed between SS bellow and absorber.

*A.Saini*

# S-matrix model (K.Bane, SLAC)

At a number of discrete frequencies, 4, 8, 12, 16, 20 and 40 GHz, we used the field solver to calculate the scattering matrix for each element type (cavity, bellows, drifts and absorber) for all TM0n monopole modes propagating in the beam pipe at each respective frequency



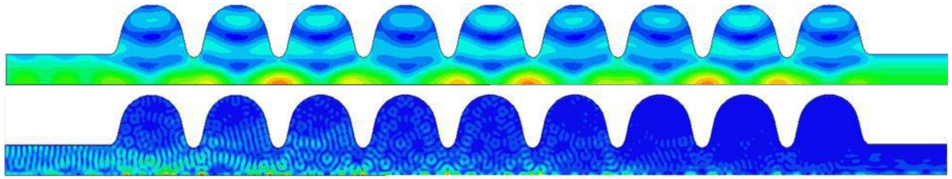
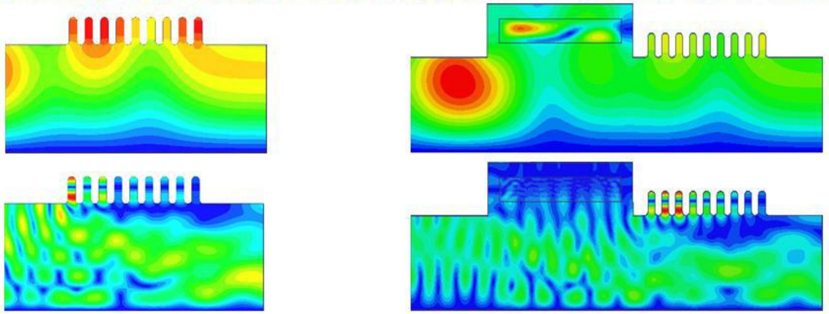



Table 1. Percent of Untrapped HOM Power to 2 K.

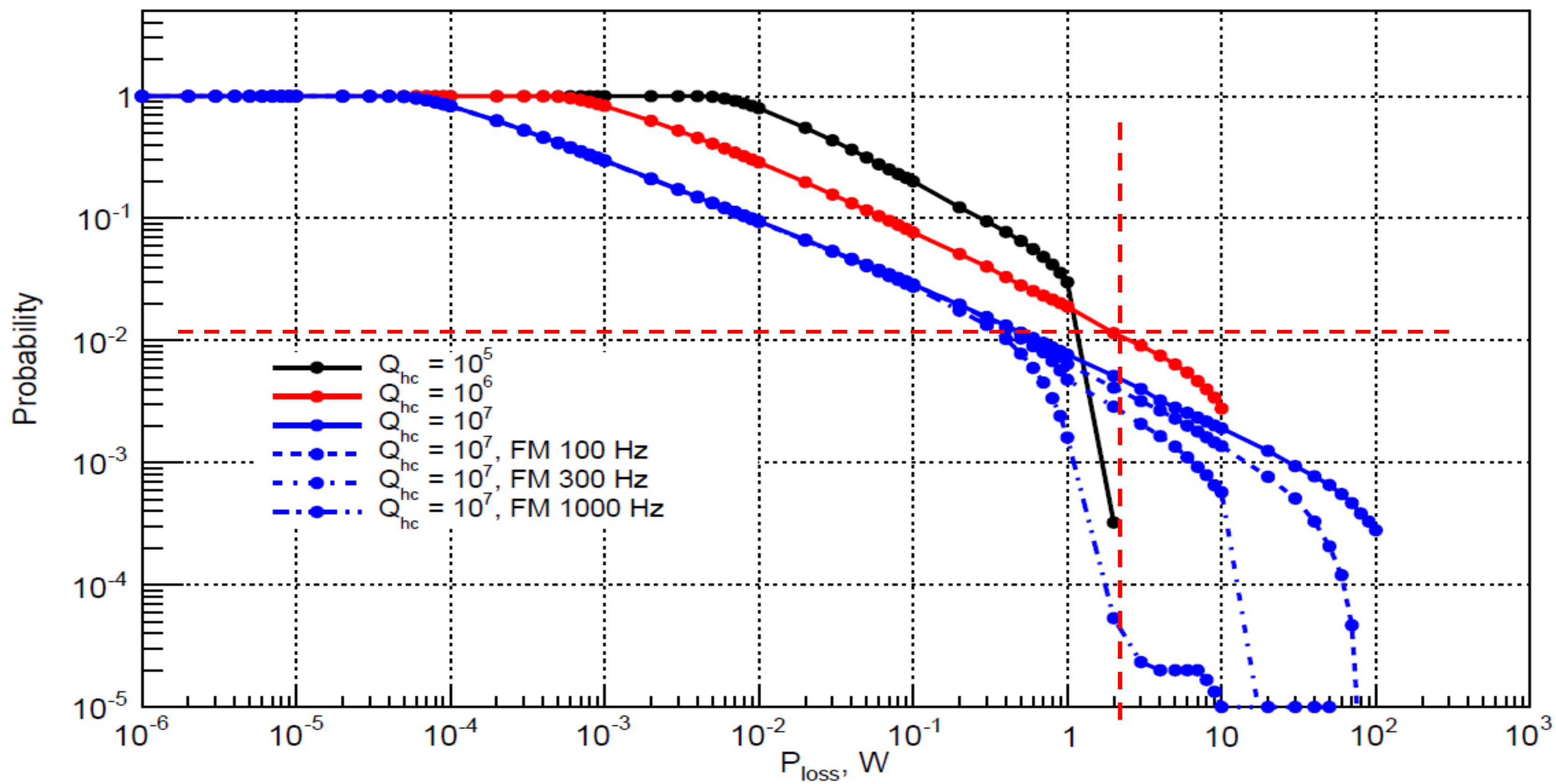
| $f$ (GHz) | Copper | | Stainless Steel | |
|---|---|---|---|---|
| | S-matrix | diffusion | S-matrix | diffusion |
| 4 | 0.75 | 0.35 | 19 | 13 |
| 8 | 3.5 | 0.55 | 49 | 18 |
| 12 | 0.5 | 0.70 | 23 | 21 |
| 16 | 0.55 | 0.85 | 10 | 24 |
| 20 | 1.1 | 1.0 | 47 | 26 |
| 40 | 1.1 | 1.6 | 35 | 33 |
| Total | | 2.7 | | 39 |



Radial geometries of the cavity, bellows and absorber with field plots (|E| for cavities; |H| for others) from HFSS simulations at 4 GHz and 20 GHz, with TM01 input from the left.

**Conclusion:** Two complementary approaches provide confidence in the effectiveness of the beamline HOM absorbers. Only a few percent HOM power will be lost at 2K.

# Maximum RF power in HOM coupler




- Only Non-propagating modes (f<2.9 GHz)
- Copper plated bellow (137 mm long)
- Random variation of HOM frequencies with 1 MHz R.M.S.

# Summary (R.Stanek – FNAL project Leader)

- FNAL has capabilities in all aspects of SRF technology and cryogenics ➔ *FNAL LCLS II Team is technically very strong*
- LCLS II scope of work is well defined and consistent with FNAL's recent SRF experience (XFEL/ILC style CM)
- This is a busy time for us as we finish design & design verification tests, prepare LLP, move into project mode, prepare for CD-2/3…
  - *Team is responding positively to the challenges*

- SRF Collaboration (with JLab and Cornell) is working well
- At FNAL, support for LCLS II is positive "across the board"

  SC => OHEP => FNAL Director => Divisions/Departments => to the shop floor

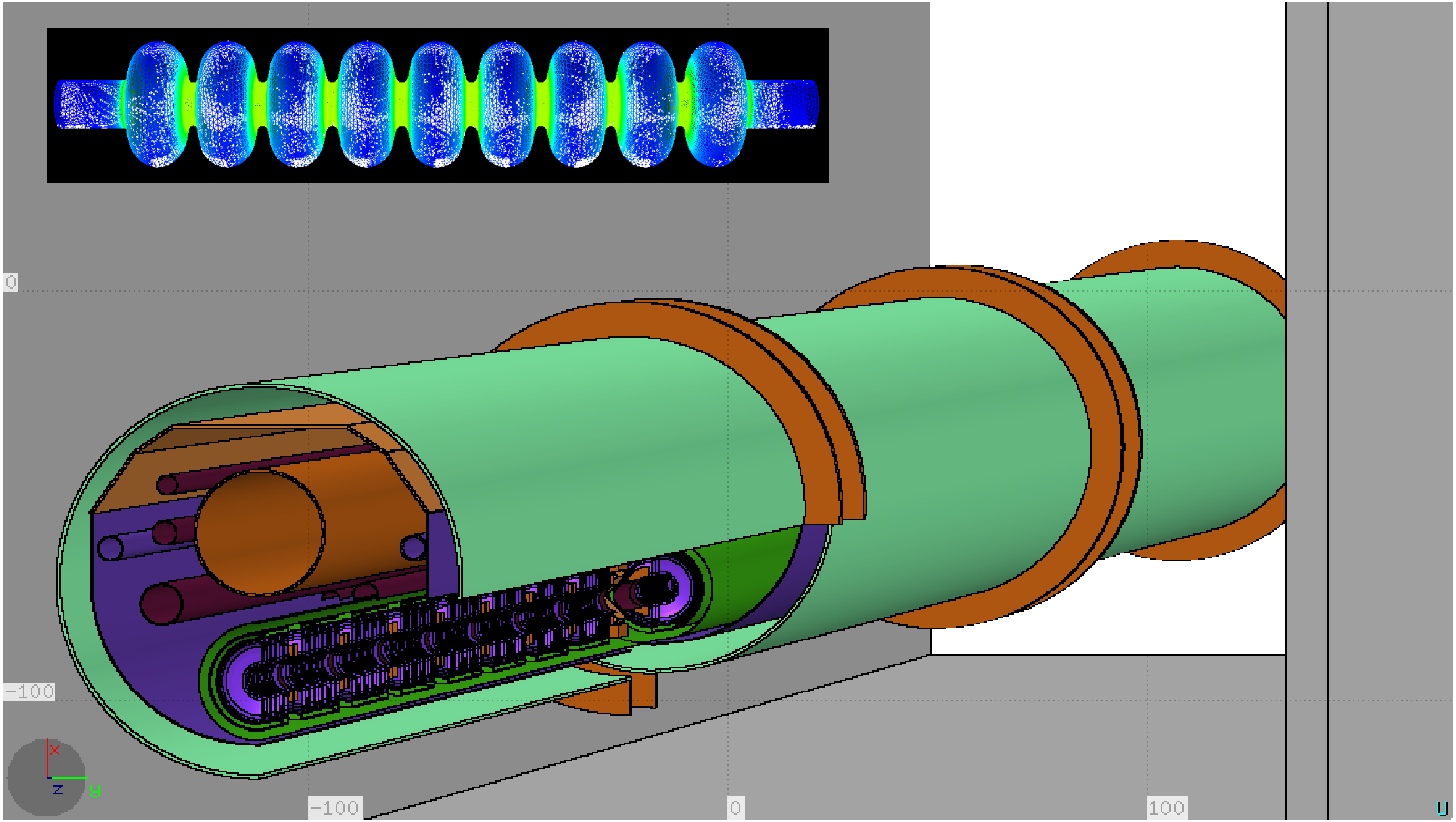
- ***FNAL is committed to making LCLS-II a success***

## Summation ( J.Galayda, LCLS-II project Leader)

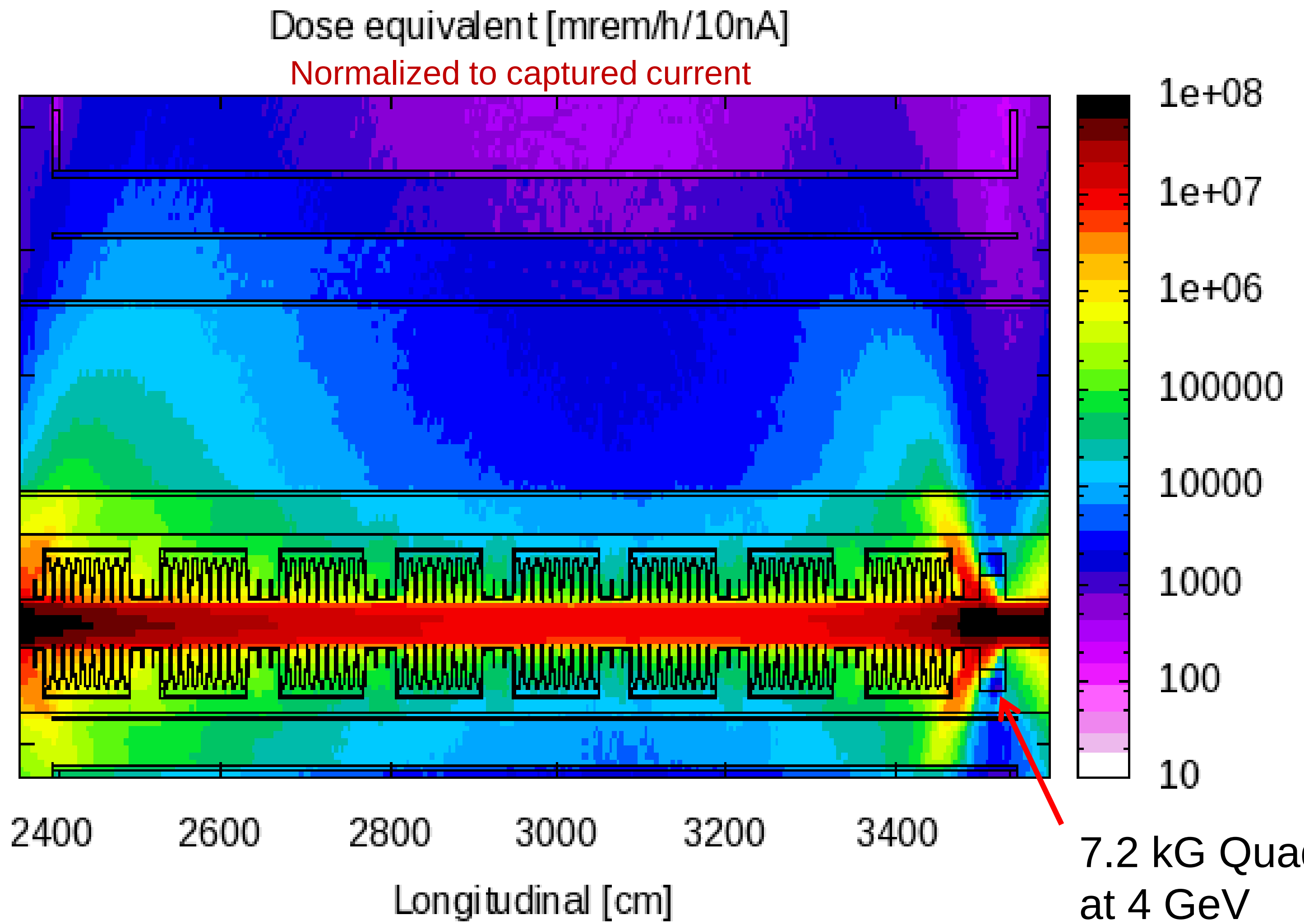
- The project has progressed rapidly
  - Mature design
  - Solid project plan
- The organization is functioning very effectively
- Technical risks are identified and handled in a technically sound way that supports the project schedule
- The project and collaboration are ready to proceed with major LLPs

# Back-up slides

# Simulation of Dark Current Generation, Propagation and Losses in the LCLS-II Linac



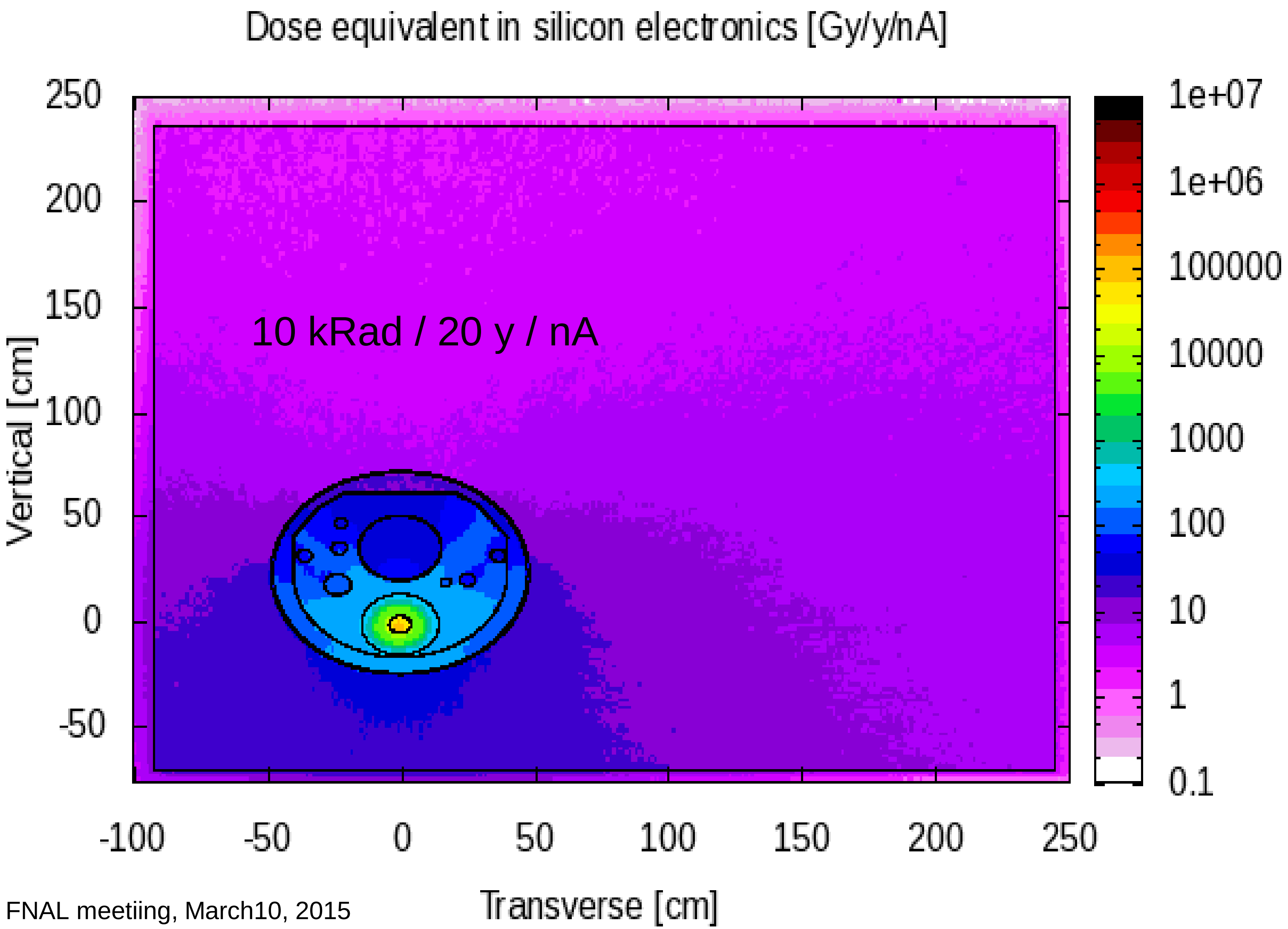
# Computed Dose In and Around a CM




7.2 kG Quad at 4 GeV

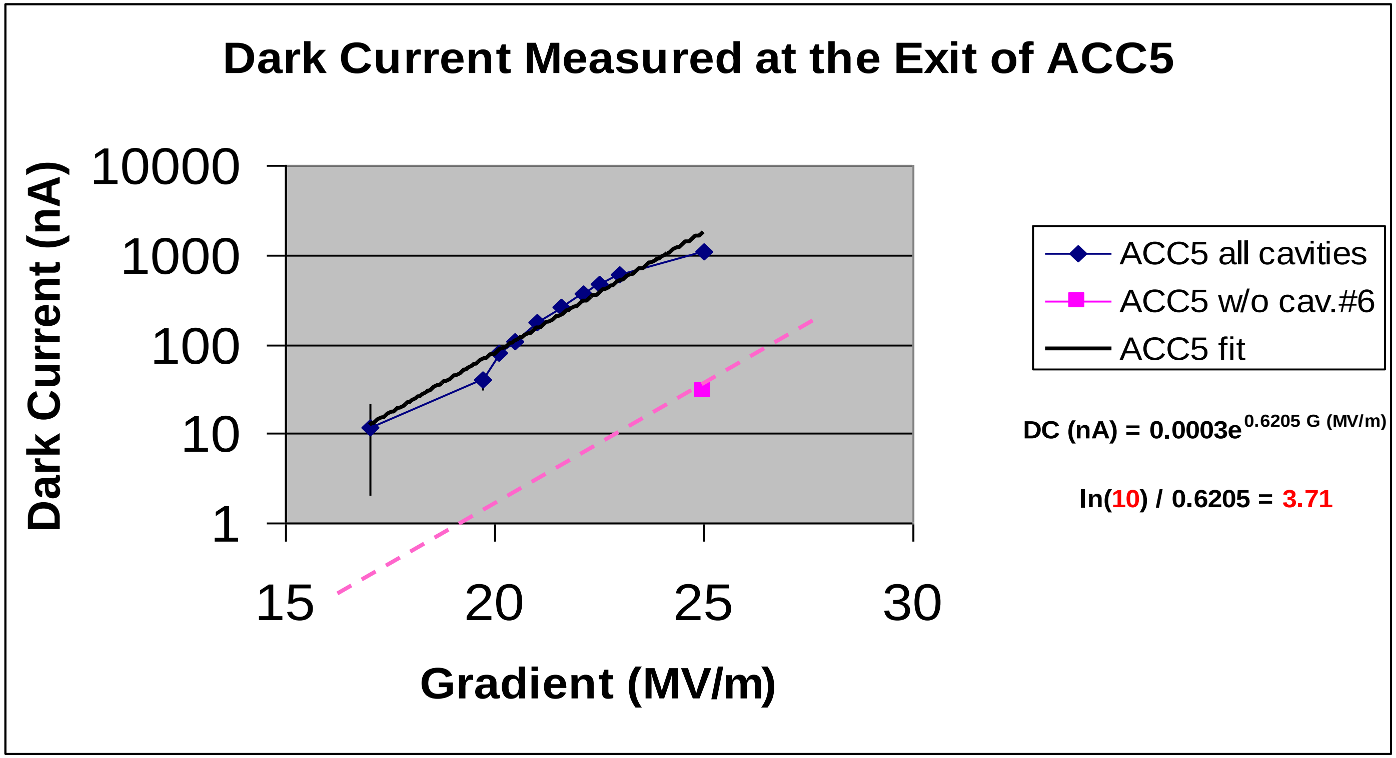
Dark Blue ~ 100 mRad / hour / nA, Red ~ 1 kRrad / hour / nA

# End View – Lower Radiation Levels above CM



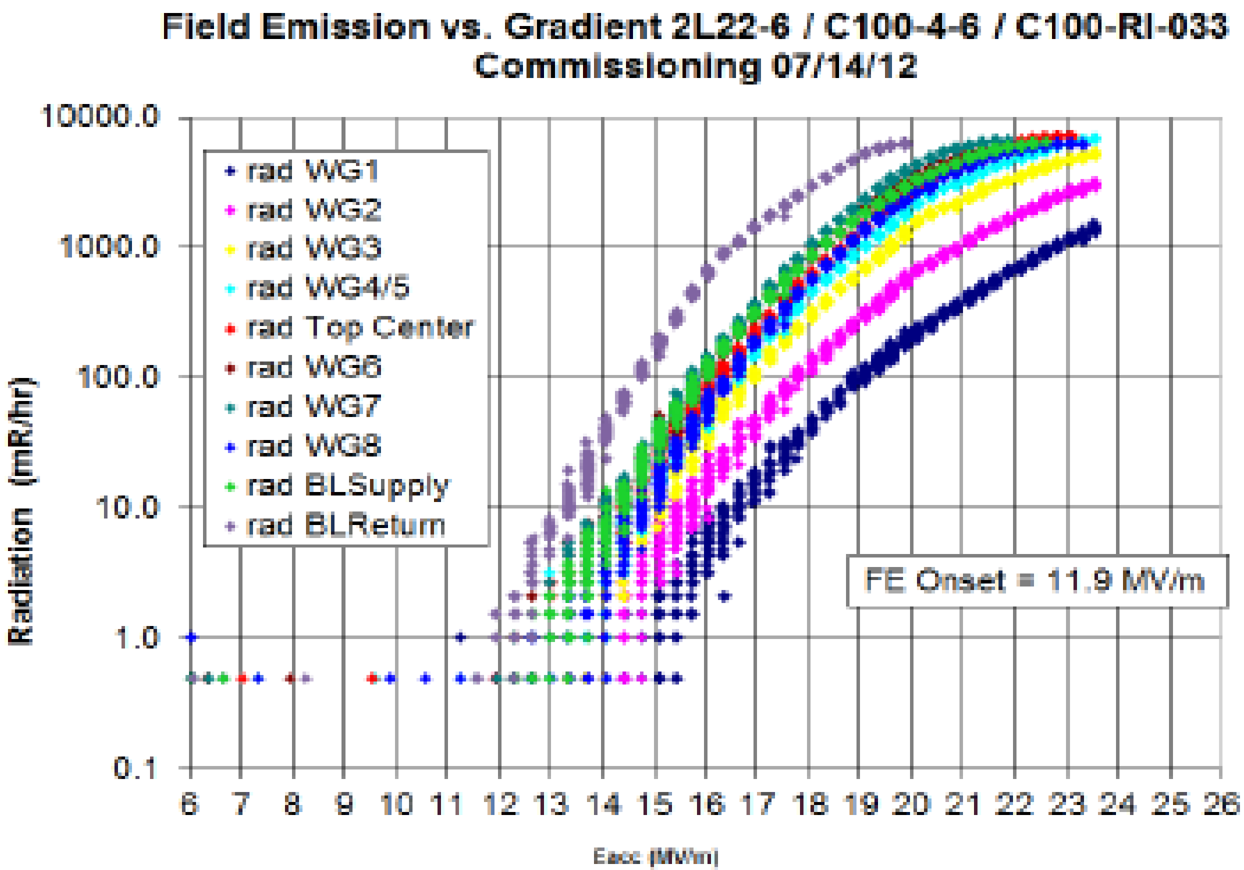
# Cryomodule Dark Current Measurements

DESY 2004 CM measurements with and without a ‘hot’ cavity detuned




Measure ~ 1 Rad/hr CW equivalent at 25 MV/m, 2.5 m from CM with hot cavity off – roughly what we would expect for the level of dark current they observe.

# JLAB and FNAL Cavity Measurements




100 nA

10 nA

1 nA

0.1 nA

Captured current estimate based on tunnel radiation levels and our simulation results

An FNAL HTS test last August concluded "we do not see radiation coming from the cavity at the noise level (~2mR/hr) [up to about 20 MV/m]". Also do not see dark currents below 20 MV/m in CM2

| Level 1 Baseline Milestones | Schedule |
|---|---|
| CD-0 - Approve Mission Need | 4/22/2010 (Actual) |
| Mission Need Statement (Update) | 9/27/2013 (Actual) |
| CD-1 - Approve Alt. Select. & Cost Range | 10/14/2011 (Actual) |
| CD-3a(1) - Approve Long Lead Procurement (LLP) | 3/14/2012 (Actual) |
| CD-1 - Approve Alt. Select. & Cost Range (Update) | 8/26/2014 (Actual) |
| Advanced Procurement of Niobium Material | 8/26/2014 (Actual) |
| CD-3b(2)- Approve LLP | 3QFY2015 |
| CD-2 – Approve Performance Baseline | 2QFY2016 |
| CD-3 – Approve Construction Start | 2QFY2016 |
| CD-4 - Project Complete/Start of Operations | 4QFY2021 |

(1)CD-3a LLP for the original LCLS-II scope; authorization included Linac Sector 10 injector and annex, undulator magnet blocks, and Global Interface System.

(2)CD-3b LLP authorizes long-lead procurements proposed at this review.

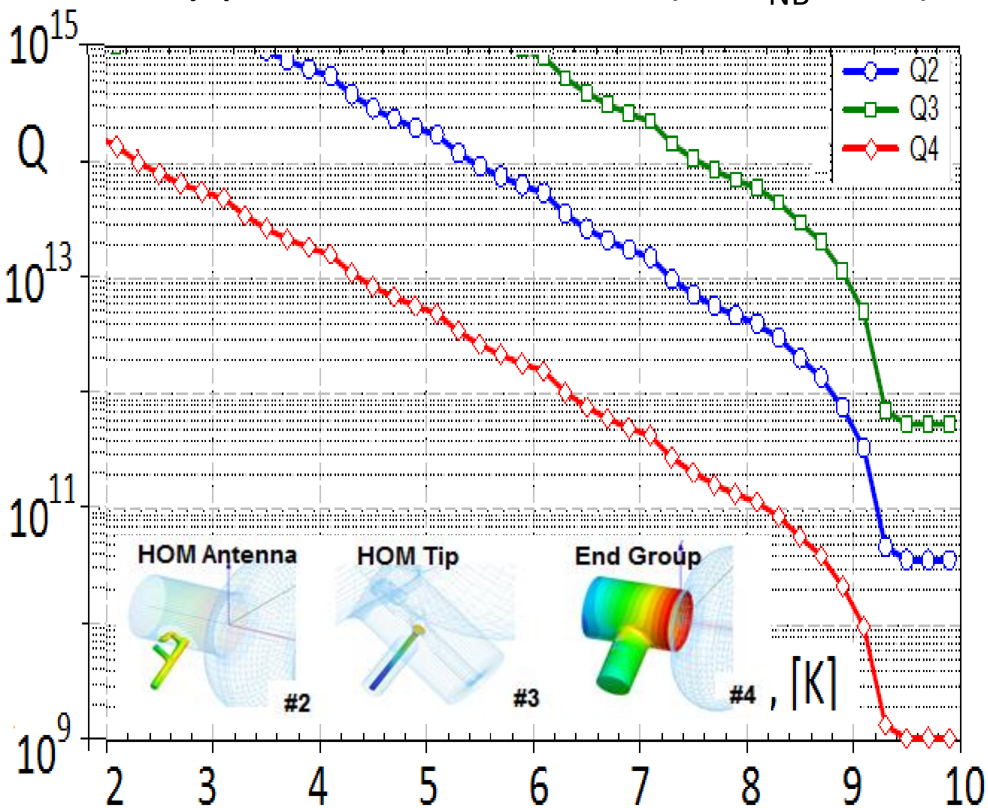
# LLP List (Greater than $500K)

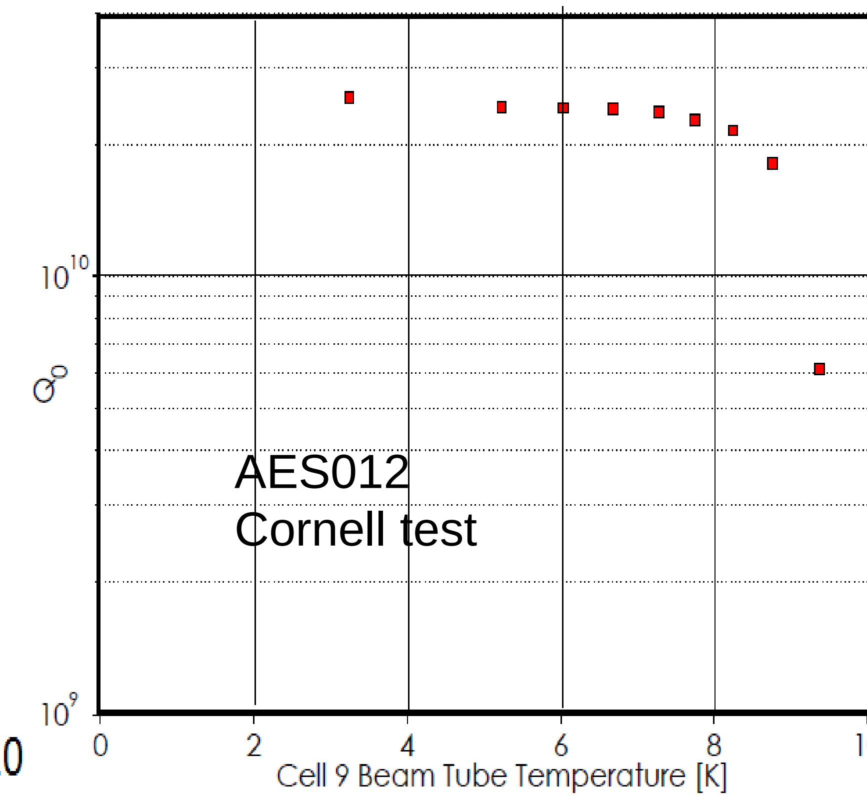
| Description | Gating Review Date | Basis of Cost Estimate at DOE Review |
|---|---|---|
| **1.04.05 Cryomodule - FNAL** | | |
| AWARD: Contract [CM_PPROD_CH_1060] Cavity String Hardware | Apr-2015 | Cost Estimate |
| AWARD: Contract [CM_PPROD_MA_1060] Magnets | Apr-2015 | Bids in Hand |
| AWARD: Contract [CM_PPROD_MS_1060] Magnetic Shielding | Apr-2015 | Cost Estimate |
| AWARD: Contract [CM_PPROD_GR_1070] GHRP Sub-assemblies | Apr-2015 | Cost Estimate |
| AWARD: Contract [CM_PPROD_VV_1070] Vacuum Vessels | Apr-2015 | Cost Estimate |
| AWARD: Contract [CM_PPROD_IN_1070] Instrumentation | Apr-2015 | Bids in Hand |
| AWARD: Contract [CM_PPROD_BM_1070] Beamline Interconnect Parts | Apr-2015 | Cost Estimate |
| AWARD: Contract [CM_PPROD_PL_1070] Coupler Pumping Lines | Apr-2015 | Cost Estimate |
| AWARD: Contract [CM_PPROD_FC_2100] Fundamental Power Couplers | Jul-2015 | Cost Estimate |
| AWARD: Contract [CM_PPROD_CF_2060] Cavity Fabrication | Jul-2015 | Cost Estimate |
| **1.04.09 Cryo Distribution System - FNAL** | | |
| AWARD: Contract - Feed Caps | Apr-2015 | Cost Estimate |
| AWARD: Contract - Injector End Cap and L3 End Cap | Apr-2015 | Cost Estimate |
| AWARD: Transfer Line | May-2015 | Cost Estimate |

- All LLP have solid BOE that relate to recent experience on similar systems (CM-1, CM-2, ARRA procurements, multiple cryogenic installations…)

# Effect of end-group Temperature on cavity Q0

Cavity parts Q-factors vs. T ($RRR_{NB}$=300)




Simulations are consistent with Cornell group measurements (`2nΩ contribution from hot beampipe at $T_{pipe}$=8K)

Q0 @ 2.0 K and 10 MV/m as a function of beam tube temperature for HTC9-2 (http://arxiv.org/pdf/1411.1659.pdf).